Evaluation of Missile Aerodynamic Characteristics Using Rapid Prediction Techniques

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A general overview of missile aerodynamic predictive methodology is made. Nine state-of-the-art rapid prediction codes are surveyed, and the NSWC Aeroprediction and NEAR Missile II codes are selected for detailed evaluation. The abilities and weaknesses of the codes to predict six-component aerodynamics of a diverse range of missile configurations (Sparrow III, Army Generalized, Maverick, and WASP) are examined. In general, both codes compared favorably in predicting longitudinal aerodynamics for angles of attack less than 10-15 deg. Both codes possess state-of-the-art and compatible methodology bases. Recommendations are given for an improved aerodynamic prediction code for future missiles.

Introduction

PRELIMINARY design and aerodynamic assessment of current and future missile configurations require a rapid, reasonably accurate method to predict aerodynamic characteristics. Three different methods can be employed to determine aerodynamics, namely: 1) wind tunnel and ballistic range tests, 2) handbook techniques, and 3), aerodynamic prediction codes. This paper deals with method 3, where well accepted predictive codes are considered.

Two different approaches can be employed to calculate aerodynamic characteristics using aerodynamic predictive methods: computational fluid dynamics using numerical techniques, and rapid engineering approximate codes using semiempirical and analytical methods. The first approach utilizes numerical schemes to solve the complete flowfield equations and can accept quite general freestream conditions and body geometries. In principle, the results obtained are more accurate than those obtained using the second approach; however, numerical methods require considerable computational time and cost and their accuracy depends on selected numerical grid sizes. These difficulties have limited their applications to engineering problems where rapid design tools are needed.

The second approach employs approximate linear and nonlinear analyses as well as experimental data. Most of the coded classical techniques have been proved over the years as representative aerodynamic predictive methods. However, a considerable amount of research is still needed to improve and extend these predictive tools. In general, the areas of necessary improvement include better accuracy, extended scope of applicability, ease of usage, and code robustness. Two distinct techniques constitute the bulk of this approach; namely, the component buildup and paneling techniques.

The current study deals with rapid aerodynamic prediction codes most suitable for preliminary engineering application, design, and evaluation. The objectives are: 1) to evaluate candidate state-of-the-art codes and select the most comprehensive codes for tactical missile applications, 2) to evaluate results of selected aerodynamic predictive codes against a large variety of realistic missile geometries using experimental data, 3) to define the capabilities, useful ranges, and limitations of these codes, and 4) to make recommendations for improvement and extension necessary to develop an advanced rapid Missile Aerodynamic Prediction (MAP) capability for generalized axisymmetric missile configurations.

Survey of Methods

The nine state-of-the-art rapid aerodynamic design and analysis computer codes and 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 II),[13] Hughes AEROP I,[14] and Air Force Digital DATCOM.[15] Each of these aerodynamic predictive methods has individual merits and weaknesses. Several techniques share basic methodologies in computing aerodynamic coefficients. In the past, missiles typically operated at low speeds and were not very maneuverable (with relatively small angles of attack). The advanced missile systems projected for the 1990s must be capable of speeds up to Mach 8, have greater maneuverability with angles of attack as high as 45 deg, and be designed for minimum drag and operation at long ranges. Consequently, technology requirements demand an individual computer code which is capable of estimating six-compo .t aerodynamic coefficients of generalized axisymmetric tactical missiles (symmetrical wing-body-tail geometries) for subsonic (Mach 0 to 0.6), transonic (Mach 0.6 to 1.2), and supersonic (Mach 1.2 to 8) speed regimes, angles of attack of up to 45 deg, all aerodynamic roll angles, and individual control surface deflections of up to 30 deg. This unified missile aerodynamics prediction capability does not currently exist. Therefore, these nine engineering methods were studied in order to select the codes that possess the most complete analytical basis (supplemented with empirical data only when necessary) that can satisfy the technological requirements. Rather than reconstructing a similar code based on classical techniques, a better code can be developed by further research as well as improving and extending the selected baseline codes. Figure 1 summarizes the nine available methods surveyed in this study. The capability of each method is shown as a function of Mach number and angle-of-attack range. The angle-of-attack range contains the normal prediction range of the code and the range applicable only to special cases such as body-alone configurations. Several

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codes, such as SHABP and APAS II (normally operable only in the small-angle-of-attack range), may provide computed results up to $\alpha = 180$ deg. However, these latter results must be used with care.

One may further classify these nine prediction methods as 1) high-angle-of-attack, 2) arbitrary body, and 3) axisymmetric missile methods (see Fig. 1). These methods are summarized with emphasis on axisymmetric configurations. Further information can be found in Ref. 16.

High-Angle-of-Attack Codes

The NASA Jorgensen,[12] AEDC Baker,[9] and Army/Martin Marietta[10,11] codes are three high-angle-of-attack semiempirical engineering methods that can estimate longitudinal aerodynamic coefficients of slender bodies with tails and/or wings (within their data bases) for angles of attack up to 180 deg. The NASA Jorgensen method computes C_N and C_m for bodies of both noncircular (not arbitrary) and circular cross sections with two sets of thin lifting surfaces. These codes lack the extensive analytical bases for constructing a generalized wing-body-tail prediction capability, including control deflections and roll-dependent aerodynamics. However, they provide a high-angle-of-attack foundation for special applications such as the Airslew-type missile which is composed of a body-tail geometry and maneuvers up to $\alpha = 180$ deg.

Arbitrary Body Codes

Three engineering codes that can handle arbitrary-shaped nonaxisymmetric configurations (see Fig. 2) and are utilized primarily for aircraft preliminary design purposes are the USAF/McDonnell Douglas Digital DATCOM (Data Compendium),[15] USAF/McDonnell Douglas SHABP,[8] and NASA/Rockwell International APAS II.[13]

The USAF Digital DATCOM is the computerized version of the well-known DATCOM which is a large data compendium of techniques, both empirical and analytical, with emphasis on aircraft stability and control derivatives. The predicted coefficients are restricted to freestream conditions and geometry for the configurations considered.

The USAF SHABP analyzes arbitrary-shaped configurations by employing a variety of noninterfering constant-pressure finite element methods. An arbitrary configuration is approximated by a system of planar panels and various supersonic (and hypersonic) methods can be selected by the user to find the "local slope" pressure distribution acting on the panel.

APAS II contains an excellent graphic capability for configuration input, editing, and display of results. By extending the original Woodward linearized subsonic-supersonic paneling method, incorporating the SHABP, and developing an interactive graphic capability, the latest APAS II code was developed.

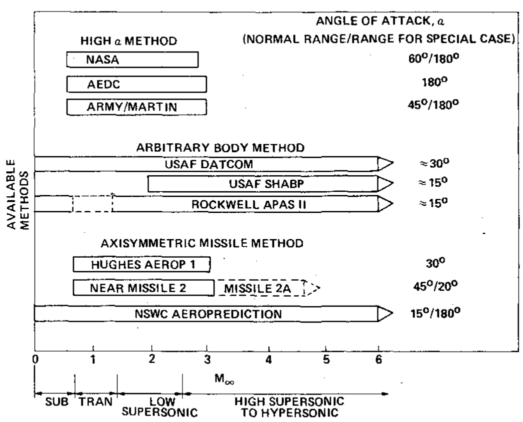

Fig. 1 Current rapid (approximate) aerodynamic prediction methods.

A code that can provide reasonably accurate pressure loading and six-component aerodynamics for arbitrary-shaped missile configurations (such as airbreathing missiles) with flight conditions of $0 \leq M_\infty \leq 8$, 0 deg $\leq \alpha \leq 45$ deg, 0 deg $\leq \phi \leq 180$ deg, and 0 deg $\leq \delta \leq 30$ deg, does not exist. In order to keep up with technological needs (for example, lifting body missile aerodynamics), research must be conducted to improve areas such as transonic, roll-dependent, and high-angle-of-attack aerodynamics. Ease of usage and reliability of arbitrary body aerodynamic predictions should also be evaluated.

Axisymmetric Missile Codes

The majority of missiles in the world weapon arsenal are composed of axisymmetric configurations (see Fig. 3) with wings (or canard control), body, and tails (or tail control). The importance of such geometries will continue into the 1990s. Three state-of-the-art methodologies include Hughes AEROP I, NEAR Missile II, and NSWC Aeroprediction.

The Hughes AEROP I data base includes a massive amount of wind tunnel data and offers 170 combinations of nose shapes, body fineness ratios, and wing and tail aspect ratios in flowfields from Mach 0.6 to 3. Over the years these data have been utilized in the preliminary design of various Hughes missiles, including the Electro-Optical (EO) and Infrared (IR) Maverick, WASP, AMRAAM, and in studies such as the Air-to-Surface Technology Study. The AEROP I data base is valid primarily within its experimental data range. Current advanced missile geometries and flight regimes are exceeding the range of parameters of AEROP I.

The strength of the Missile I code[6] is its unique capability to handle higher angles of attack and roll-dependent aerodynamics. In this model, the afterbody-generated vorticity, which originates from flow separation, is represented by two

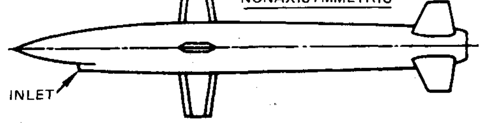

Fig. 2 Typical missile geometries.

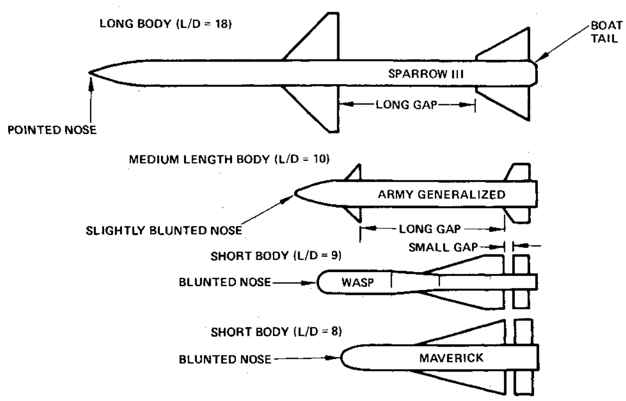

Fig. 3 Missile geometries depicting large variation of external shapes.

point vortices of the opposite sign located one on each side of the body. It was found that better prediction could be obtained by using two distributed regions of many discrete vortices called "vortex clouds." The incorporation of the vortex cloud theory along with some other changes has generated the Missile II code.[7] This code utilizes a data base augmented by analysis, is applicable over a Mach range of 0.8 through 3.0 with angles of attack up to 45 deg, and allows arbitrary roll angles and control deflections. The calculation of loads on a fin utilizes a correlation method that is based upon the nonlinear equivalent angle-of-attack approach. This approach relates the forces experienced by the surface formed by placing two opposing fins together in the absence of the body to the actual fin in the presence of the body.

The weaknesses of the Missile II code are: 1) maximum aspect ratios are 2 and 4 for Mach regions 1.3-3.0 and 0.8-1.3, respectively; 2) only clipped delta fins are allowed; 3) lack of zero-lift drag coefficient estimation; 4) unsuitable for handling highly blunted or truncated noses; and 5) the geometrical variations and freestream conditions are far less general than the Aeroprediction code.

Currently, an interim computer program, Missile IIA, that may handle Mach numbers up to 5.0, fin aspect ratios up to 5, and angles of attack and fin deflections up to 20 deg has been developed. This data base was extended by an analytical procedure using body-alone Euler finite difference solutions, shock-expansion strip theory, wing-alone data, and extrapolation. The data base is being extended further using wind tunnel testing in a program sponsored by Triservices and NASA. The validity of Missile IIA should be tested against several missile geometries.

The Aeroprediction code can handle axisymmetric wing-body-tail combinations. The geometry has been kept as general as possible (see Fig. 2). Williams[17] evaluated the Aeroprediction code and concluded that it is a computer program employing the best available methods for computing aerodynamic characteristics of missiles. The body is composed of the cylindrical afterbody and boattail/flare. The nose can be pointed, spherically blunted, or truncated. A maximum of two discontinuities in slope is allowed along the nose. The lifting surfaces consist of canard (or wing) and tail with deflection allowed. They may have biconvex or general modified double-wedge airfoil sections. The leading and trailing edges can be sharp, truncated, or blunted. For the general case, the code is limited to roll-independent ($\phi = 0$ deg) aerodynamic coefficients for subsonic, transonic, and supersonic speeds up to Mach 8 at small angles of attack. For the special cases this code can estimate body-alone and body-tail longitudinal aerodynamics up to higher angles of attack (0 deg $\leq \alpha \leq 45$ deg for body-tail combinations at $\phi = 0$-180 deg; 0 deg $\leq \alpha \leq 180$ deg, for isolated components, $\phi = 0$ deg, using Army/Martin Marietta high α code). However, missile applications should include the more general case of wing-body-tail configurations, and special case limitations should be removed.

The methods used to compute inviscid body-alone aerodynamics include the improved second-order shock expansion, the hybrid theory by Van Dyke and Tsien, the Wu and Aoyoma/Euler code, and Spring and Gwin's empiricisms for high supersonic, low supersonic, transonic, and subsonic speeds, respectively. The viscous cross-flow effects are treated by Allen and Perkins' cross-flow theory, while friction drag is calculated by means of the Van Driest II flat-plate theory. No pressure gradient effects due to geometrical variation are included in calculating subsonic drag.

The aerodynamic surfaces are handled by using lifting surface theory, DATCOM empiricism, linear theory, and tangent wedge theory for subsonic, transonic, low supersonic, and high supersonic speeds, respectively. The Pitts-Nielsen-Kaatari method is used to calculate wing-body interference effects excluding high supersonic speeds. No control surface unporting effect due to flow spillage through gaps is included.

Since there are no vortex effects included, predictions at angles of attack larger than 10-15 deg may be less representative. The transonic wave drag and normal force coefficient based on limited extrapolation of the Euler solution are expected to be weak.

Although the Aeroprediction and the Missile II codes have weaknesses, they possess extensive and compatible theoretical/experimental methodology bases for axisymmetric tactical missile applications. The combined usage, as well as the improvement and extension of these two codes, can lead to a generalized missile aerodynamics prediction capability. For the above reasons, this study evaluates the Aeroprediction and Missile II codes in detail by evaluating them individually against experimental data.

Discussion of Results

Several researchers have presented evaluations of various computational codes using only one type of missile geometry.[18-21] Such geometries are usually composed of nearly pointed noses, slender afterbodies, and two sets of lifting surfaces. To provide a general and realistic validation of these two codes against wind tunnel data, a diverse set of four missiles composed of varied nose shapes, body lengths, wing shapes, and wing-tail gap distances were chosen (see Fig. 3). These missiles are Sparrow III, Army Generalized, Maverick, and WASP. There are no stated aspect ratio limitations in the Aeroprediction code; however, the Missile II code requires that the aspect ratio be less than 2 for $M_\infty = 1.3$ to 3.0. By maintaining the sweepback angle and surface area constant, decreasing the span, and increasing the chord slightly, modified control surfaces for Sparrow III, Maverick,

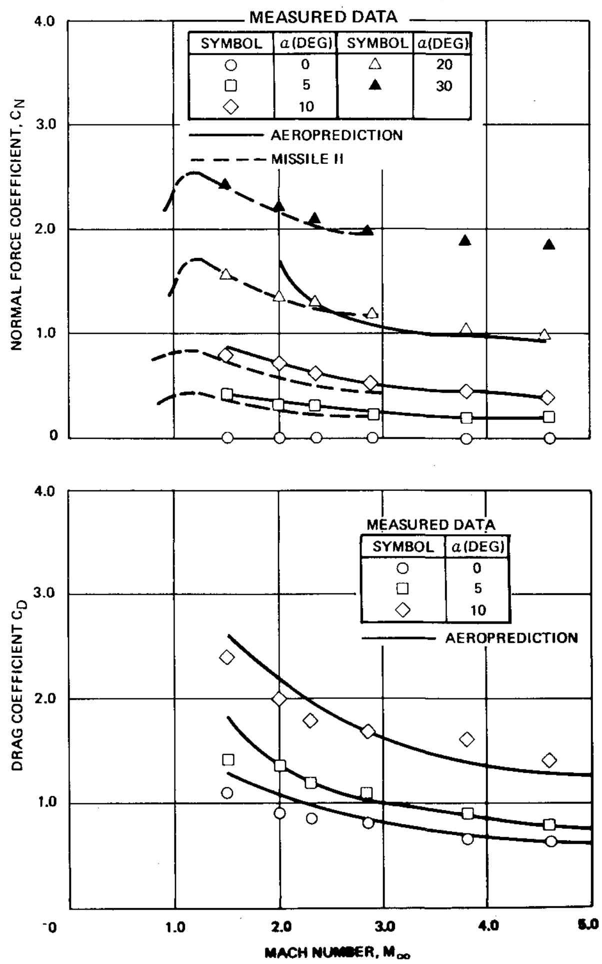

Fig. 4 Comparison of normal force and drag coefficients for Sparrow III missile, $\phi = 0$ deg.

and WASP were employed which fit Missile II requirements. This method was used to closely simulate the wing configurations so that the Missile II code could be examined on realistic missile shapes.

Six-component aerodynamic coefficients were computed and compared with experimental data. More extensive comparisons can be found in Ref. 16. Comments are made whenever appropriate to describe the capabilities, strengths, and weaknesses of both codes in predicting the six-component aerodynamics of missiles with large configurational variances. Additional evaluation and recommendations for specific areas of improvement and extension are also included.

Sparrow III

The Sparrow III configuration was considered as an extreme case due to its long, slender-body shape, pointed nose, relatively high aspect ratio wing, and long gap between lifting surfaces.

The normal force and drag coefficients are shown compared with wind tunnel data[20] in Fig. 4. Both prediction methods compare favorably at lower angles of attack ($\alpha \leq 10$ deg) within the tested Mach regime. At higher angles of attack (10 deg $\leq \alpha \leq 30$ deg), the Missile II code prediction of normal force coefficient continues to give good results, while the Aeroprediction code compares less favorably. The Aeroprediction code can calculate longitudinal aerodynamics throughout the entire Mach range of interest, i.e., $0 \leq M_\infty \leq 8$; whereas the Missile II code is limited between Mach 0.8 and 3.0.

The drag comparison with Aeroprediction is good (Missile II does not predict drag), as shown in Fig. 4. Pitch moments were plotted as a function of angle of attack for $M_\infty = 2.0$. Figure 5 shows that the comparisons between theories and data for pitching moment coefficients are less agreeable as the angle of attack increases.

The normal and side force coefficients are shown compared with wind tunnel data [20] in Fig. 6. The comparison of Missile II against data is shown for a roll angle of $\phi = 26.6$ deg and a Mach number of $M_\infty = 2.0$. The experimental data show that the side force is much smaller than the normal force. The predicted side force is in reasonable agreement with the test data, particularly in relation to the magnitude of the normal force and its prediction. The pitching, yawing, and rolling moments are plotted in Fig. 7. Agreement between theory and data for both yawing and pitching moment are fair at angles of attack below 20 deg. At a fixed roll angle, the prediction fails to capture the trends of the data as the angle of attack increases. For rolling moment, agreement is good at moderate angles of attack (20 deg), but poor at other angles. Hence the trend of the prediction is questionable.

Army Generalized Missile

The Army Generalized Missile[7] can be considered as a typical missile shape with a slightly blunted ogive nose, medium length body, and long gap between two sets of lifting surfaces. This configuration provides an excellent means of comparing the prediction capabilities of both codes.

The Army Generalized Missile longitudinal aerodynamic characteristics were predicted and compared with wind tunnel data[21,22] in Figs. 8 and 9. Published test results are available at only two transonic Mach numbers. Therefore, no subsonic and supersonic comparisons are shown here. It is interesting that the general conclusions are similar to those for Sparrow III. Both codes compare favorably for normal force coefficients at small angles of attack, below 10 deg. The comparisons for drag coefficient for the Army Generalized Missile are not presented due to the unavailability of experimental data. However, all other results show that the Aeroprediction code provides good drag prediction at supersonic speeds. Both codes give favorable pitching moment comparison with data at low angle of attack in the transonic range ($M_\infty = 1.3$). However, similar results obtained in the subsonic range ($M_\infty = 0.8$) show lesser agreement. The longitudinal, lateral, and rolling aerodynamic characteristics as a function of angle of attack are predicted and compared with data in Figs. 10 and 11 at roll angle $\phi = 20$ deg and Mach

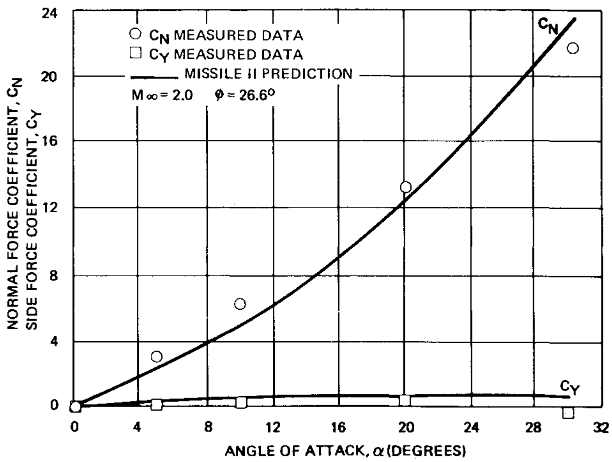

Fig. 6 Comparison of C_N and C_Y for Sparrow III missile; $\phi = 26.6$ deg, $M_\infty = 2.0$.

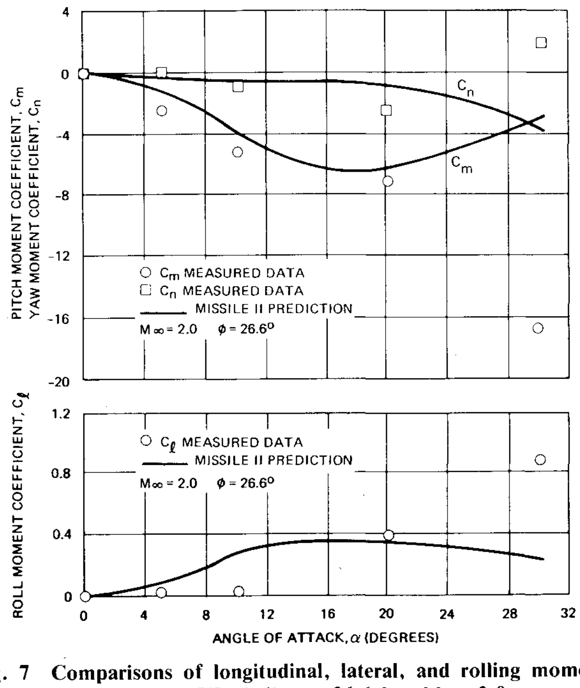

Fig. 7 Comparisons of longitudinal, lateral, and rolling moment coefficients for Sparrow III missile; $\phi = 26.6$ deg, $M_\infty = 2.0$.

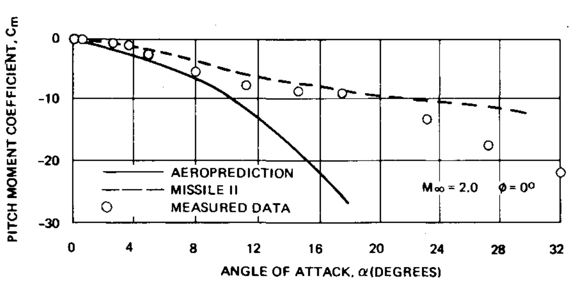

Fig. 5 Comparison of pitching moment coefficient for Sparrow III missile; $\phi = 0$ deg, $M_\infty = 2.0$.

number $M_\infty = 1.3$. Comparisons of normal force coefficients against data are considered good for preliminary missile design purposes. Side force coefficients are in reasonable agreement with the test data. Pitching, yawing, and rolling moment coefficients are in reasonable agreement at angles of attack below 10 deg; however, their accuracy decreases as angle of attack increases.

Maverick Missile

The Hughes Maverick missile can be considered another extreme case when compared to the Sparrow III configuration. Maverick possesses a highly blunted nose and a very short body. The gap between the two sets of lifting surfaces is very narrow, which causes significant vortex interference effects. The test data are available in Refs. 23 and 24. Figure 12 shows the Aeroprediction code producing better normal force agreement with the test data than the Missile II code, particularly at supersonic speeds.

The Aeroprediction code provides good supersonic drag prediction, but less accurate results in the transonic speed regime. As a function of angle of attack at $M_\infty = 1.3$, the pitching moment coefficients show good agreement with the Aeroprediction code (Fig. 13). The normal and side force coefficients are presented as a function of angle of attack in Fig. 14. Here, comparisons are made at a roll angle of $\phi = 22.5$ deg and a Mach number of $M_\infty = 1.3$. The prediction of normal force and side force coefficients is fair.

The pitching, yawing, and rolling moment coefficients are presented in Fig. 15 as a function of angle of attack at $\phi = 22.5$ deg. The pitching moment coefficient compares well against data at $M_\infty = 1.3$. The yawing moment coefficients show fair agreement at $\alpha \leq 16$ deg. The trend in rolling moment prediction as a function of angle of attack is generally poor. At angles of attack less than 30 deg, the side force coefficient is often less than 10% of the magnitude of the normal force coefficient, and the yawing moment coefficient is usually less than 30% of the pitching moment coefficient. This is especially true in the linear range of angle of attack (0 deg $\leq \alpha \leq 10$ deg) where vortex effects on the lateral aerodynamics are small. During the preliminary design phase, more emphasis is often placed on the prediction of longitudinal rather than lateral and rolling aerodynamics.

WASP Missile

The Hughes WASP missile represents another missile geometry variation. It has a blunted-nose, narrowed-down afterbody resembling an extremely long boattail, and a small gap separating two sets of lifting surfaces.

A comparison of the longitudinal aerodynamic coefficients (C_N, C_m, and C_D) of the WASP missile is summarized in Fig. 16.[25] The predicted results using the Aeroprediction and Missile II codes are plotted as a function of Mach number. The Aeroprediction code provides a good comparison for supersonic drag prediction, but is less accurate at both transonic and subsonic speeds. It also provides reasonably good comparisons between normal force and pitching moment coefficients for angles of attack less than 10 and 5 deg, respectively. For the WASP missile, the Missile II code is less accurate in predicting the normal force coefficient, but slightly better in predicting the pitching moment coefficient.

In summary, both the Aeroprediction and Missile II codes generally demonstrate good agreement with wind tunnel data in predicting longitudinal aerodynamic coefficients for angles of attack less than 10-15 deg and at zero roll angle. Furthermore, the Aeroprediction code often produces a slightly better prediction than the Missile II code at small angles of attack. The Missile II code can provide aerodynamic estimations up to 45 deg angle of attack, whereas the Aeroprediction code breaks down at approximately $\alpha = 20$ deg. However, the uncertainty of Missile II in predicting accurate aerodynamic coefficients increases for $\alpha \geq 15$-20 deg and at $\phi \neq 0$ deg.

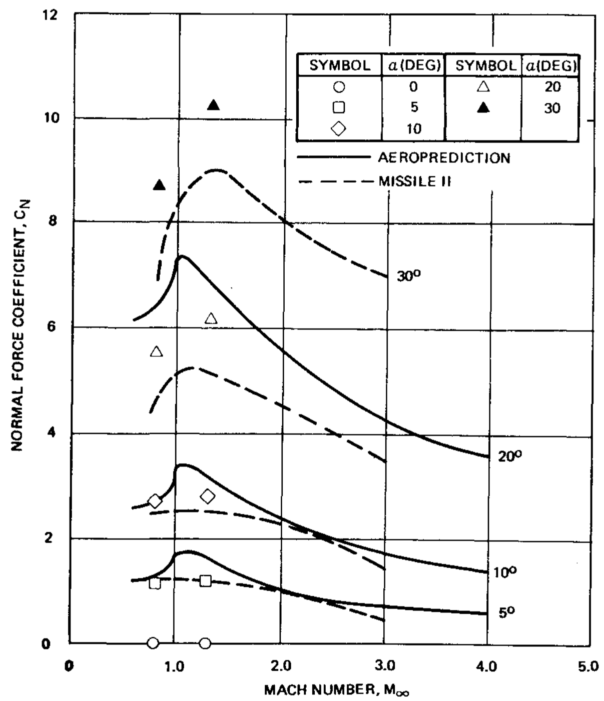

Fig. 8 Comparison of normal force for Army Generalized Missile, $\phi = 0$ deg.

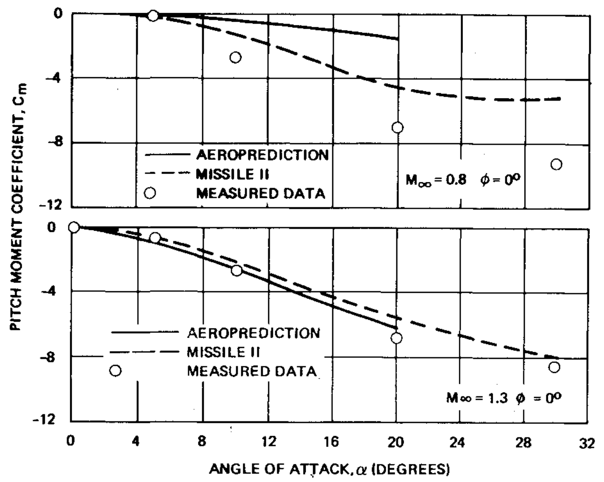

Fig. 9 Comparisons of pitching moment coefficients for Army Generalized Missile; $\phi = 0$ deg, $M_\infty = 0.8, 1.3$.

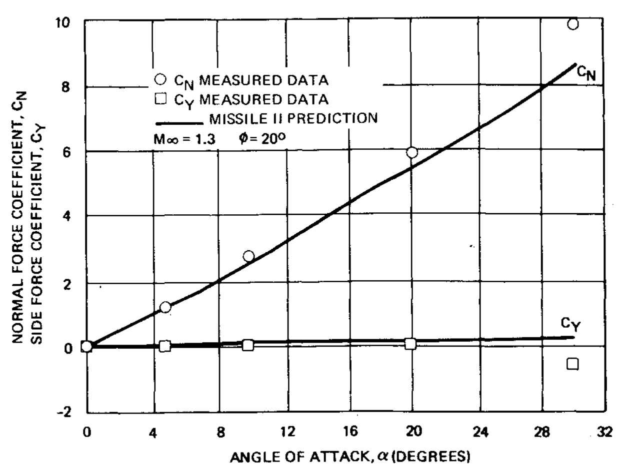

Fig. 10 Comparisons of C_N and C_Y for Army Generalized Missile; $\phi = 20$ deg, $M_\infty = 1.3$.

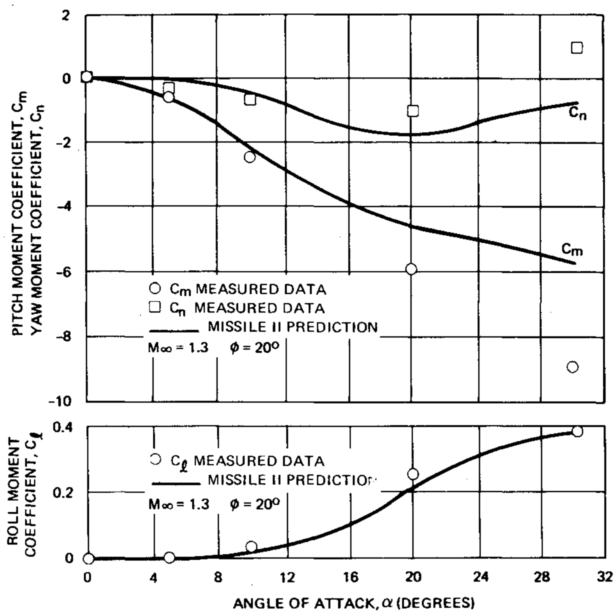

Fig. 11 Comparisons of longitudinal, lateral, and rolling moment coefficients for Army Generalized Missile; $\phi = 20$ deg, $M_\infty = 1.3$.

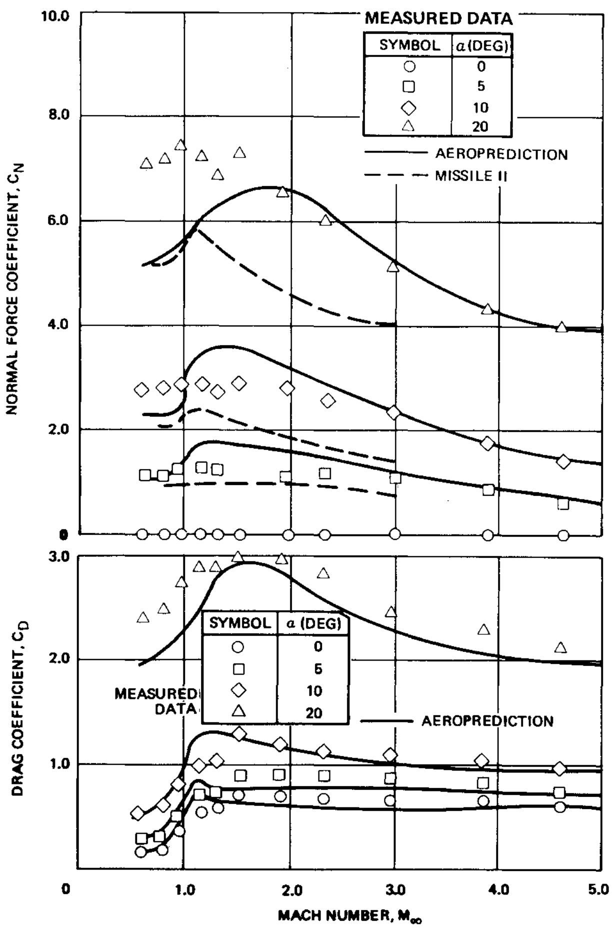

Fig. 12 Comparisons of normal force and drag coefficients for Maverick missile, $\phi = 0$ deg.

In terms of six-component coefficients, the Aeroprediction and Missile II codes generally provide good estimations of normal force coefficients, with occasional mixed results in transonic speeds. The Aeroprediction code gives good supersonic drag prediction, but less accurate results in both the transonic and subsonic speed regimes. Good to fair results

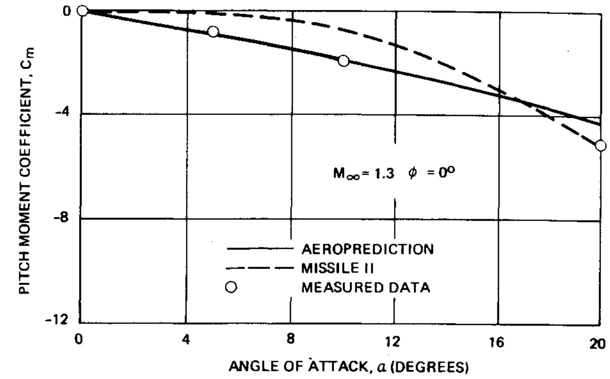

Fig. 13 Comparisons of pitching moment coefficient for Maverick missile; $\phi = 0$ deg, $M_\infty = 1.3$.

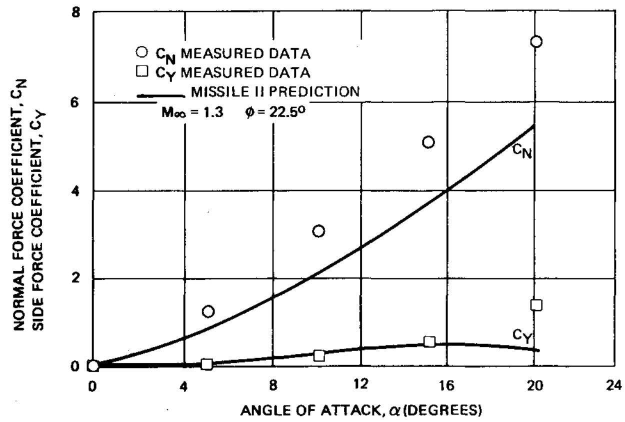

Fig. 14 Comparisons of C_N and C_Y for Maverick missile; $\phi = 22.5$ deg, $M_\infty = 1.3$.

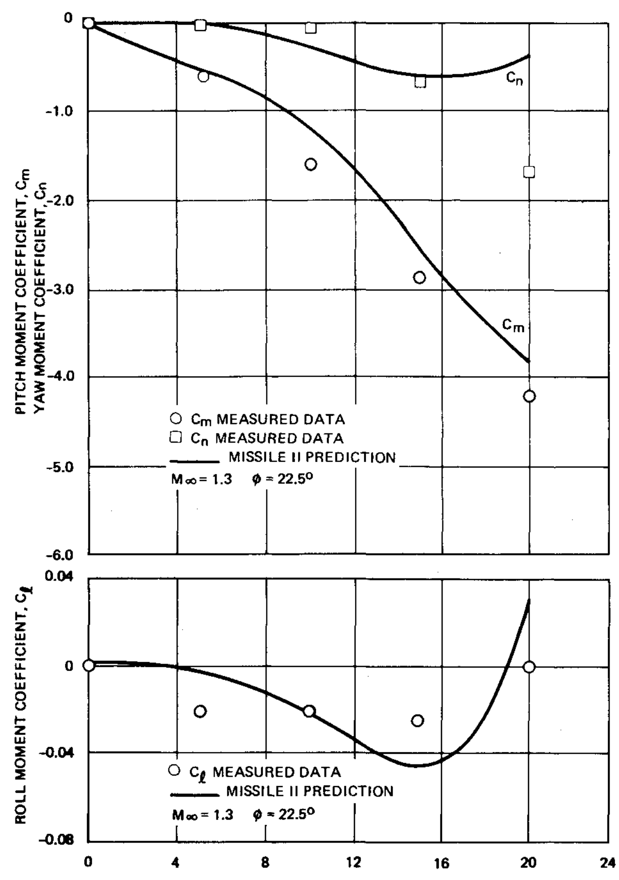

Fig. 15 Comparisons of longitudinal, lateral, and rolling moment coefficients for Maverick missile; $\phi = 22.5$ deg, $M_\infty = 1.3$.

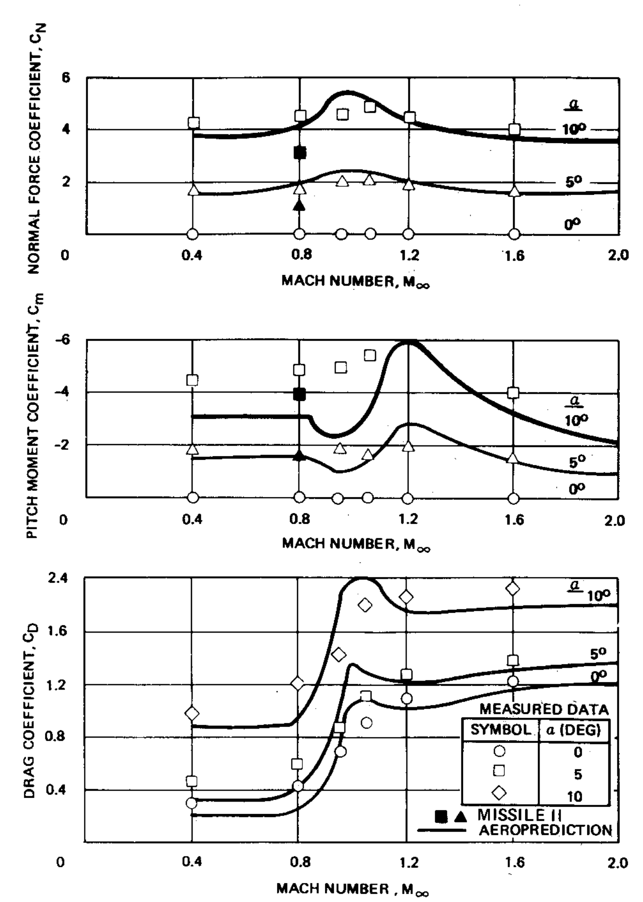

Fig. 16 Comparisons of normal force, pitching moment, and drag coefficients for WASP missile, $\phi = 0$ deg.

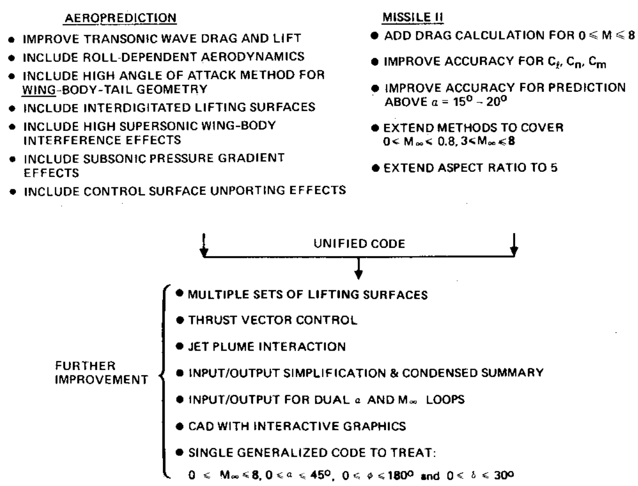

Fig. 17 Recommended technological extension and improvement.

have been obtained for pitching moment and side force coefficients. The Missile II prediction of both yawing and rolling moment coefficients is generally less reliable as a function of angle of attack. However, during preliminary design phases more emphasis is placed on longitudinal coefficients than lateral and rolling coefficients. Both codes possess compatible methodology bases for predicting aerodynamic coefficients; therefore, by sharing the predictive methodology, removing the weaknesses, improving the accuracy, and extending the scope of prediction, a better code can be obtained.

Conclusions and Recommendations

This study identifies both the Aeroprediction and Missile II codes as the two most comprehensive and compatible state-of-the-art methodologies for treating axisymmetric wing-body-tail aerodynamic characteristics. The combined and intelligent usage of both codes (knowing their strengths and weaknesses) can serve as a valuable preliminary design and evaluation tool. In general, both codes demonstrate favorable agreement with wind tunnel data in predicting longitudinal aerodynamics for zero roll angle and angles of attack less than 10-15 deg. Above $\alpha = 15$-20 deg and at fixed roll angles, the uncertainty of Missile II in predicting aerodynamic coefficients increases. Based on the results obtained in this study and the projection of future needs, recommended areas of improvement and extension are summarized in Fig. 17 and listed below.

1) Since the Aeroprediction and Missile II codes are compatible and complementary, the basic theoretical/experimental methodologies can be unified and shared. The improvement of accuracy, extension of prediction scope, and improvement of software robustness can lead to a better code for generalized axisymmetric missiles. Furthermore, computer-aided design (CAD) capability with interactive graphical display of engineering geometries and computational results must be developed and input/output simplicity must also be considered.

2) The Missile II prediction accuracy of C_l, C_n, and C_m is generally less reliable at arbitrary roll angles and should be improved. The aspect ratio, nose contour, and Mach number restriction should also be relaxed so that generalized missile configurations can be handled up to Mach 8.

3) The reliability of Missile II in predicting all coefficients decreases as the angle of attack increases above $\alpha = 15$-20 deg. Improvement of prediction accuracy in the higher angle-of-attack regime is needed.

4) The high-angle-of-attack technique employed in the Aeroprediction code is limited to body-alone or body-tail combinations. The majority of current and future advanced missiles employ a minimum of two sets of lifting surfaces. Consequently, the current Aeroprediction code is useful only in the angle-of-attack range of $0 \text{ deg} \leq \alpha \leq 15$ deg. Furthermore, it cannot handle aerodynamics with interdigitated lifting surfaces and at arbitrary roll orientations. By including techniques such as vortex cloud theory and equivalent angles of attack described in the Missile II methodology, the Aeroprediction code then can be generalized in the treatment of high-angle-of-attack and roll-dependent aerodynamics.

5) The Aeroprediction code is weak in its treatment of transonic wave drag and lift coefficients as well as subsonic drag. However, its accuracy can be improved by using a data base obtained from transonic relaxation methods, transonic empirical data, and including subsonic pressure gradient effects, respectively.[26,27]

6) When control surfaces deflect, gaps are created between the root chord and the body. The Aeroprediction code significantly overestimates both the lifting and pitching moment coefficients for missiles with large control surface deflections. Improvement of prediction accuracy can be achieved by including loss of control surface effectiveness due to unporting (or gap) effects.[28]

7) Advanced missile concepts require that prediction codes handle three sets of lifting surfaces: forward canards, aft canards, and tails. The Magic R-550 missile, capable of making fast response and large maneuvers, is a typical example. Therefore, rapid prediction codes should be modified to handle multiple sets of lifting surfaces.

8) At high supersonic speeds only the improved second-order shock expansion theory and tangent wedge strip theory are applied to the body and lifting surfaces, respectively. The Aeroprediction code should include accurate wing-body interference effects in its calculation of high-speed

aerodynamics, particularly when the lift carryover area is large.

9) When designs of fast response, highly maneuverable missiles are achieved through propulsion systems, the research and development of thrust vector control and jet plume interaction models should be included in the existing codes.

By improving, extending, and unifying the technological bases contained in both the Aeroprediction and Missile II codes, a generalized rapid prediction code that is capable of estimating six-component aerodynamic coefficients for $0 \leq M_\infty \leq 8$, 0 deg $\leq \alpha \leq 45$ deg, all ϕ, and 0 deg $\leq \delta \leq 30$ deg can be developed.

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