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Comparison of Analytical and Experimental Supersonic Aerodynamic Characteristics of a Forward Control Missile

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Techniques to predict the aerodynamic characteristics of slender cruciform missiles have been developed and are constantly being updated and improved. This paper presents comparisons between analytical and experimental supersonic aerodynamic data for a class of canard-controlled missile configurations similar to the Sidewinder missile. Three aerodynamic prediction computer codes, including program MISSILE2, a recently improved version of program MISSILE, are evaluated by comparison with the test data to assess their accuracy. The major emphasis is placed on the roll control characteristics. In addition, tail span optimization, longitudinal and lateral control, induced roll, and missile roll orientation effects are addressed. Roll control is shown to be feasible on a Sidewinder-class missile by reducing the tail span. Program MISSILE2 provides improved rolling moment predictions over program MISSILE, however, further improvements appear needed. Program DEMON2 provides excellent low-angle-of-attack rolling moment predictions and is superior to the other two programs at higher angles of attack.

Nomenclature

AR	= fin aspect ratio = $4(b/2)/(C_R + C_T)$
$b/2$	= exposed fin semispan
C_ℓ	= rolling moment coefficient = rolling moment/$(q_\infty S_{\mathrm{ref}} \ell_{\mathrm{ref}})$
C_m	= pitching moment coefficient = pitching moment / $(q_\infty S_{\mathrm{ref}} l_{\mathrm{ref}})$
C_n	= yawing moment coefficient = yawing moment/$(q_\infty S \ell_{\mathrm{ref}})$
C_N	= normal force coefficient = normal force/$(q_\infty S_{\mathrm{ref}})$
C_R	= fin root chord
C_T	= fin tip chord
C_Y	= side force coefficient = side force/$(q_\infty S_{\mathrm{ref}})$
d	= body diameter
ℓ_{ref}	= reference length (body diameter)
L	= body length
M_∞	= freestream Mach number
S_{ref}	= reference area = $\pi d^2/4$
q_∞	= freestream dynamic pressure
X_{CG}	= moment reference center from model nose
α	= angle of attack
δ	= canard deflection angle
δ_R	= total roll control deflection angle for horizontal canards, sum of both deflection angles on each canard
δ_Y	= canard yaw control deflection angle (vertical canards only), average of both deflection angles
ϕ	= roll angle

Introduction

IN a previous study[1] Blair and Rapp reported on the results of an investigation in which aerodynamic test data on several variations of the basic Sidewinder airframe (Fig. 1) were obtained and compared in two recently developed aerodynamic prediction programs—program MISSILE and program DEMON2 (the latter called program VORTEX TRACKING by Blair and Rapp).

The test data of Ref. 1 indicated the possibility of roll control benefits to be gained by reducing the tail span of the Sidewinder missile; however, the test did not contain a systematic variation of tail span, so no definite conclusions on this possible benefit could be made.

The paper also contained roll control comparisons between the test data and the predictions from program MISSILE. A sample of this comparison is included in Fig. 1 and shows fair agreement between the two at zero angle of attack, but a diverging trend with angle of attack. The predictions were so bad that Blair and Rapp suggested that some errors must certainly be contained in program MISSILE.

In each of the three configurations tested by Blair and Rapp, however, the aspect ratio of either the canard or tail fins, or both, lay outside the range of validity of the data base on which program MISSILE is based (Fig. 1). The predictions were, therefore, obtained for these configurations only by extrapolation of this data base, thus weakening the conclusion concerning the roll control comparisons. In fact, in an epilog contained in Ref. 1, the developers of program MISSILE responded to this conclusion by stating that they were "...confident that large errors in rolling moment are due to extrapolation outside the data base."

The present study was undertaken in an attempt to clarify these two issues raised in Ref. 1. Data were obtained on several configurations in which a systematic tail span

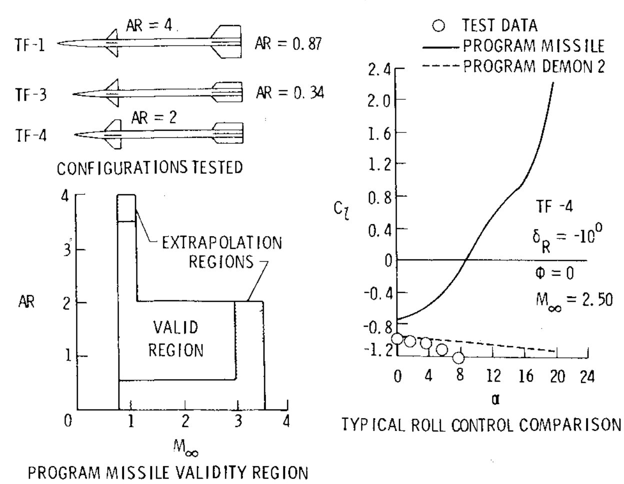

Fig. 1 Review of Blair and Rapp results.

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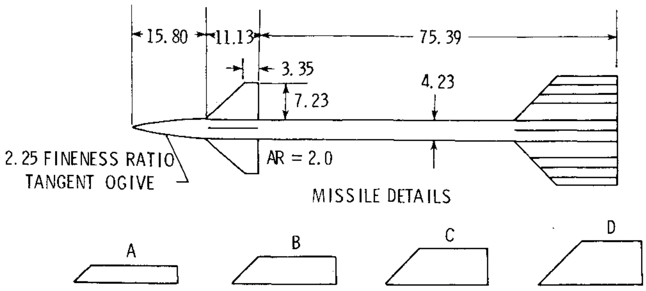

TAIL	A	B	C	D
ROOT CHORD	21.59	21.59	21.59	21.59
TIP CHORD	18.21	16.15	13.87	12.55
SEMI-SPAN	3.38	5.44	7.72	9.04
AR	0.34	0.57	0.87	1.06

TAIL FIN DETAILS

Fig. 2 Configurations tested (all dimensions in centimeters).

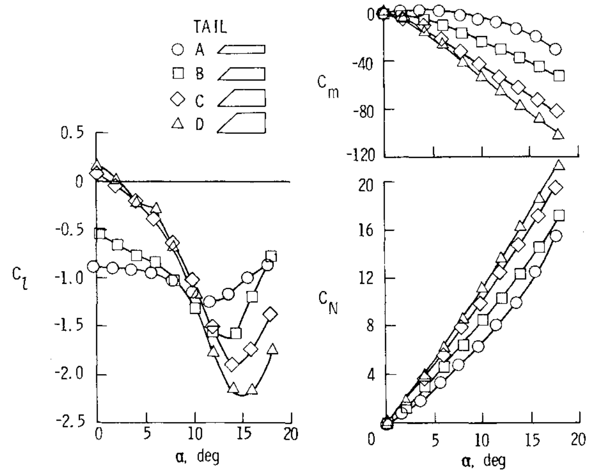

Fig. 3 Effect of tail span on roll and longitudinal characteristics ($M_\infty = 2.50$, $\delta_R = -10$ deg, $\phi = 0$ deg, $X_{CG} = 0.45\ L$).

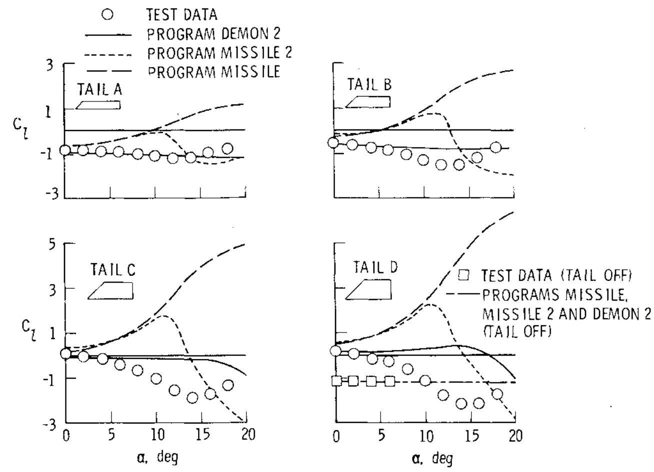

Fig. 4 Effect of tail span on roll control predictions ($M_\infty = 2.50$, $\delta_R = -10$ deg, $\phi = 0$ deg).

variation was performed to document the possible control benefits of a tail span reduction on the Sidewinder missile. Moreover, three of the four configurations tested contained fins which lay inside the region of the validity of the program MISSILE data base. Thus, comparisons between the roll control data from these configurations and the predictions from program MISSILE should answer the aspect ratio extrapolation question resulting from the Blair and Rapp paper.

Also included in this paper are predictions from program MISSILE2, which is a recently improved version of program MISSILE, the primary improvement being the inclusion of a vortex cloud model for the prediction of afterbody vorticity. Reference 2 contains a detailed description of program MISSILE2 and its differences from program MISSILE.

In addition to these two programs, rolling moment predictions are included from program DEMON2, called program VORTEX TRACKING by Blair and Rapp. Reference 3 contains the complete details of program DEMON2.

This paper thus has three objectives: One is to investigate the effects on roll control of a systematic variation of tail span on a Sidewinder-class missile. The second is to use the test data to evaluate the aerodynamic prediction capabilities of programs DEMON2, MISSILE, and MISSILE2. The third is to determine if extrapolation outside the validity range of the data base was the cause of the poor agreement between the test data and program MISSILE in the Blair and Rapp paper.

Test Data

The details of the missile and fin configurations tested in this study are shown in Fig. 2. The configurations are basically variations of the Sidewinder missile on which the canard fin chord has been lengthened to bring its aspect ratio within the range of validity required by programs MISSILE and MISSILE2, and to which several interchangeable tail fins with a common root chord have been added.

The model with tail A is the same as configuration TF-4 in the Blair and Rapp paper, while tail C is the standard Sidewinder missile tail. For the range of Mach numbers tested ($1.6 < M_\infty < 3.5$), tails B, C, and D fall within the acceptable region of aspect ratio for program MISSILE and MISSILE2 (Fig. 1), while tail A falls in the extrapolation region.

The test was conducted in both test sections of the unitary plan wind tunnel at the Langley Research Center.[4] The test Mach numbers ranged 1.6-3.5, although most of the data presented in this paper will be for Mach 2.50. The test Reynolds number based on body length was 6.7×10^6. A sting-mounted, six-component strain gage balance was used to measure the forces and moments on the various configurations. Transition strips were located on the nose of the missile and near the leading edge of all fin surfaces to assure turbulent flow over the model.

The major emphasis in this paper is placed on roll control characteristics; however, some longitudinal and lateral characteristics are presented. The model attitude parameters varied on this test include the angle of attack α, the angle of roll ϕ, and the canard fin deflection angle δ.

Effects of Tail Span on Roll Control

Figure 3 shows the effects of tail span on the experimental rolling moment characteristics for angles of attack up to about 18 deg. The Mach number for these data was 2.50, the roll angle was zero, and the two horizontal canard fins were each deflected 5 deg to give a total roll control deflection angle δ_R of -10 deg. It can be seen that the two larger tails (which include the standard Sidewinder tail) provide roll control only at the higher angles of attack. At zero angle of attack these two tails actually produce roll reversal; that is, the rolling moment, although small, is in the opposite direction than that which would be expected from the direction of the control deflections. Because of this loss of control at small angles of attack, the Sidewinder missile in operation today does not have roll control, but instead contains rollerons on the tail fins to reduce, but not eliminate, the roll rate.

Figure 3 shows, however, that as the tail span is reduced, roll control is achieved even at low angles of attack. The reason for this phenomenon is that the vortex-dominated flowfield produced by the deflected canard fins passes very close to the tail fins at low angles of attack, producing rolling moments on the tail fins of opposite sign to those created on the canard fins. For the bigger tail fins this opposite roll is large enough to counteract the roll of the canard fins, thereby producing a total roll which is negligible or, in some cases, opposite to that desired. As the tail size is reduced, however, this induced roll on the tails is also reduced, thus allowing the roll produced by the canard fins to dominate and deliver the desired total roll control.

This beneficial roll effect is not without penalty, however. As can be seen on the right side of Fig. 3, reducing the tail span results in decreases in both the normal force and pitching moment. There appears to be room for tradeoff, however. That is, the tail span of the missile can be reduced somewhat to produce roll control at low angles of attack and yet still produce adequate longitudinal characteristics.

Roll Control Predictions

Program MISSILE

The roll control predictions from all three prediction programs are shown in Fig. 4 compared with the same test data that was shown in Fig. 3. The four tail sizes are separated into different plots for clarity. Comparing the predictions of program MISSILE with the test data, it can be seen that the predictions are adequate only at very low angles of attack and quickly diverge from the data at increasing angle of attack. The tail fins of configuration A are outside the program MISSILE data base, but all fins for the other three configurations are inside; hence, this diverging trend does not appear to be caused by using program MISSILE outside its range of validity.

Program MISSILE2

Also shown in Fig. 4 are predictions from program MISSILE2, which is a recently improved version of program MISSILE. Both programs give similar predictions up to angles of attack of about 10 deg, where they quickly diverge from each other. This divergence begins at the angle where afterbody vorticity is predicted to begin by both programs. Hence, the two predicted trends above angles of attack of about 10 deg reflect the effects of the different afterbody vorticity models contained in each program.

Program MISSILE contains an afterbody vortex model which allows two concentrated vortices to develop and grow in strength along the length of the afterbody. Program MISSILE2, on the other hand, accounts for vortex growth by allowing many small vortices to develop along the length of the afterbody (vortex cloud). Thus, program MISSILE2 more accurately represents the afterbody vorticity, whose effects on the tail fins should be modeled better.

Indeed, Fig. 4 shows that program MISSILE2 does produce a roll control trend at the higher angles of attack which reverses the divergence-with-data trend that was predicted by program MISSILE. Thus, the program MISSILE2 predictions are in better agreement with the data than those from program MISSILE. The agreement is still not very good, however, and gets worse as tail size increases.

It should be emphasized that the differences between the roll control characteristics of program MISSILE, program MISSILE2, and the test data came entirely from the tail fins. This can be seen by noting from Fig. 4 that the tail-off predictions from both programs are in excellent agreement throughout the angle-of-attack range. And both are in excellent agreement with the test data, which were limited to angles of attack of less than about 6 deg for the tail-off data because of balance load limits. From these comparisons, it appears that room exists for further improvements in the tail-fin roll predictions of programs MISSILE and MISSILE2. Both of these programs make use of reverse-flow theory in the calculation of loadings on the tail fins, including the effects of canard vortices. It is possible that a program error exists in this method.

Program DEMON2

Also shown in Fig. 4 are the rolling moment predictions from program DEMON2, which contains a line source/sink and doublet method and a supersonic panel method for the calculation of body and fin pressure distributions. Program DEMON2 is, thus, a more sophisticated research tool compared to programs MISSILE and MISSILE2, which are more suitable as preliminary design and analysis tools. All three programs, however, use the same vortex tracking method.

Figure 4 shows that the rolling moment predictions from program DEMON2 are in excellent agreement with the test data at low angles of attack for all the tail sizes tested. The trend with angle of attack is also excellent for the smallest tail size, but becomes progressively worse with increasing tail size. The overall agreement with the data, however, is much better than that produced by either MISSILE or MISSILE2. The tail-off program DEMON2 predictions are seen to be in excellent agreement with the test data (and with programs MISSILE and MISSILE2). Thus, the difference between the two are the result of tail-fin predictions, which was also true, as noted earlier, for programs MISSILE and MISSILE2.

Program DEMON2, being a linear theory method, but capable of generating body and fin vortices, is limited to moderate angles of attack below about 20 deg.[3] However, afterbody vorticity is not included in this method. Figure 4 shows, however, that the difference between the predictions of program DEMON2 and the test data are sizeable only on the larger tail configurations at angles of attack above those where afterbody vorticity is predicted to occur by programs MISSILE and MISSILE2. Thus, the inclusion of afterbody vorticity in program DEMON2 could improve its rolling moment predictions at these higher angles of attack.

Effects of Mach Number at $\alpha = 0$ deg

As shown in Fig. 4, all of these programs provided fairly good rolling moment predictions at small angles of attack for all four tail sizes at Mach 2.50. Figure 5 shows the effects of Mach number on the $\alpha = 0$ deg rolling moment characteristics for all three prediction methods compared with the test data. Program DEMON2 shows very good agreement with the data throughout the range of Mach numbers and tail sizes tested. Note that the roll reversal effect, which is present in the test data for the larger tail sizes at the higher Mach numbers, is not present at the lower Mach number of 1.75. This trend is predicted very nicely by program DEMON2, but not by programs MISSILE or MISSILE2. Overall, the predictions from programs MISSILE and MISSILE2 become more accurate with increasing Mach number.

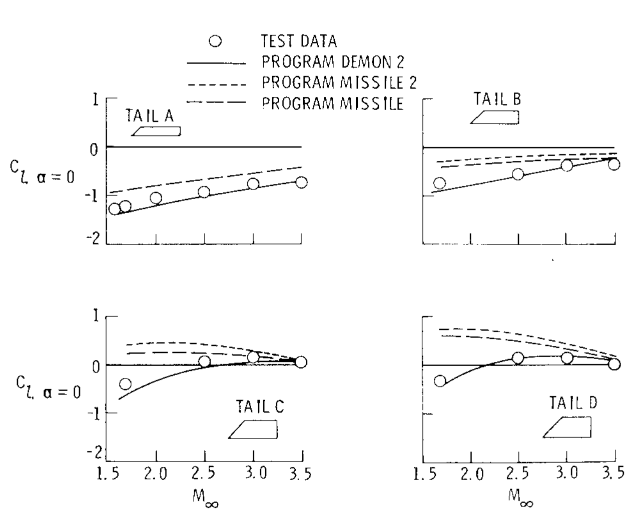

Fig. 5 Effects of Mach number on roll control at $\alpha = 0$ deg, $\phi = 0$ deg, $\delta_R = -10$ deg.

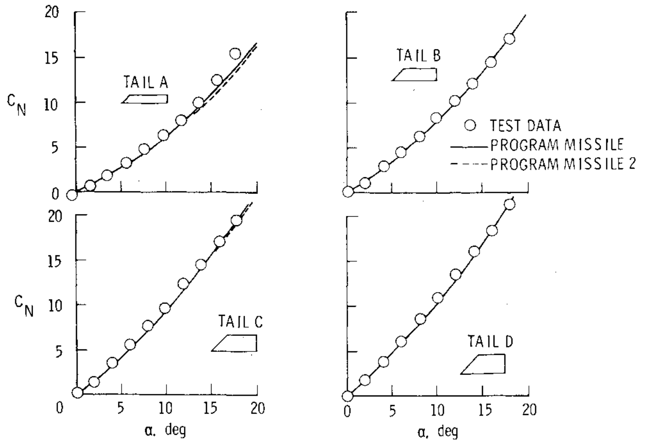

Fig. 6 Comparison of measured and predicted normal force characteristics ($M_\infty = 2.50$, $\delta_R = -10$ deg, $\phi = 0$ deg).

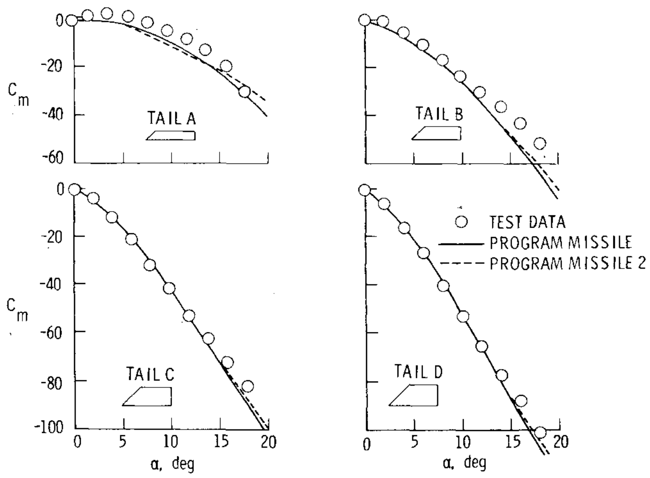

Fig. 7 Comparison of measured and predicted pitching moment characteristics ($M_\infty = 2.50$, $\delta_R = -10$ deg, $\phi = 0$ deg, $X_{CG} = 0.45\ L$).

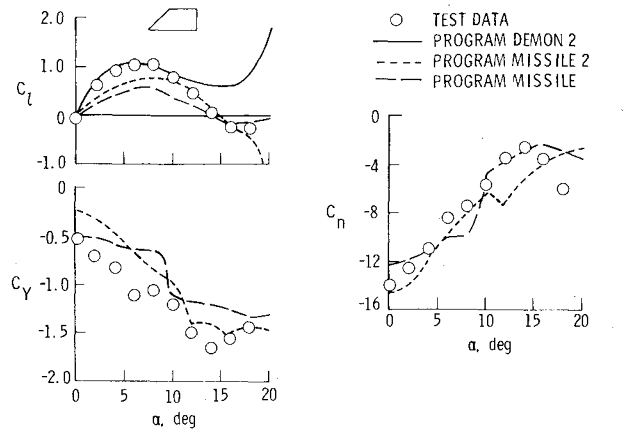

Fig. 8 Comparison of measured and predicted lateral characteristics (tail D, $M_\infty = 2.50$, $\phi = 0$ deg, $\delta_Y = 5$ deg).

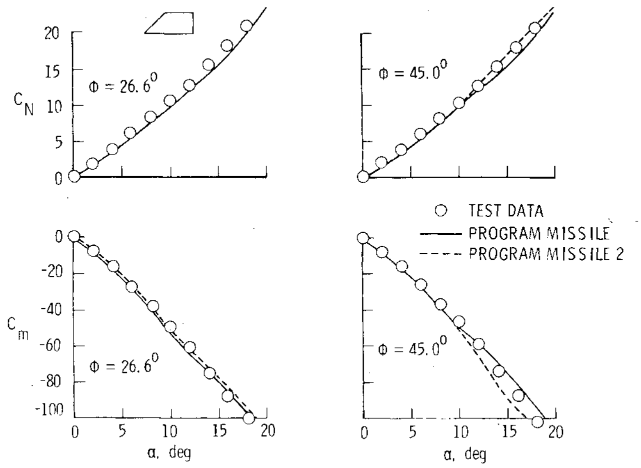

Fig. 9 Effects of missile roll orientation on longitudinal characteristics (tail D, $M_\infty = 2.50$, $\delta = 0$ deg, $X_{CG} = 0.45\ L$).

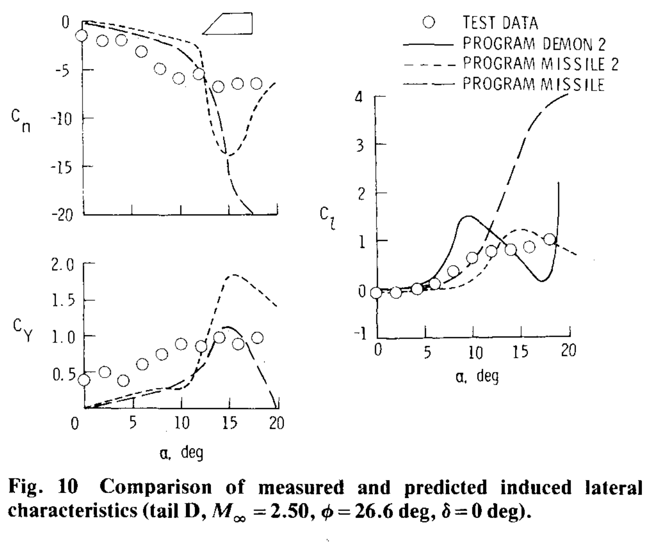

Fig. 10 Comparison of measured and predicted induced lateral characteristics (tail D, $M_\infty = 2.50$, $\phi = 26.6$ deg, $\delta = 0$ deg).

Longitudinal Characteristics

Figures 6 and 7 show the normal force and pitching moment characteristics, respectively, of the test data compared with predictions for all four tail sizes. The test conditions are the same as those previously shown in the rolling moment comparisons at a Mach number of 2.50. Note that program DEMON2 predictions are not included in these figures. In its present form, program DEMON2, does not integrate the calculated pressure distributions on the missile body and, therefore, does not provide predictions of the forces and moments on the body. Thus, only the rolling moment, which requires no body component, is available from program DEMON2 for complete missile configurations. A future version of program DEMON2 will integrate these body pressures and will thus allow prediction of the forces and moments acting on entire missile configurations.

These figures show generally very good agreement in longitudinal characteristics between the test data and the predictions of both programs MISSILE and MISSILE2, with the better agreement occurring at the larger tail sizes. The fact that the longitudinal characteristics from programs MISSILE and MISSILE2 are virtually identical and, in very good agreement with the test data, are in sharp contrast to the rolling moment characteristics shown previously in Fig. 4. Thus, for the same conditions in which rolling moment predictions show large deviations from the test data and from each other, programs MISSILE and MISSILE2 provide very accurate predictions of the longitudinal characteristics.

Lateral Characteristics

The ability of the analytical programs to predict lateral characteristics and induced roll is examined in Fig. 8. In this figure, the test data and predictions are compared for the largest tail configuration (tail D) at Mach 2.50, zero roll angle, and a yaw fin deflection of 5 deg. For this deflection angle, the horizontal canard fins are undeflected and the vertical canard fins are each deflected 5 deg. Figure 8 shows that both programs MISSILE and MISSILE2 do a fairly good job of predicting the trends of the lateral characteristics over the entire angle-of-attack range, with neither being clearly better than the other.

The predictions from program DEMON2 are included in the rolling moment plot and show excellent agreement with the data for angles of attack up to about 10 deg, where they begin to deviate sharply from the data.

This induced roll and the bumpy nature of the lateral characteristics shown in Fig. 8 are the result of the influence of the canard vortices on the tail fins. The most dominant influence results from the vortex originating at the tip of the lower canard fin, which is loaded due to its yaw deflection.

Effect of Missile Roll Orientation

Figure 9 shows the effects of missile roll orientation on the measured and predicted longitudinal characteristics for the large tail configuration (tail D), Mach 2.50, and no fin deflections. Very little effect of roll angle can be seen between programs MISSILE and MISSILE2.

The induced rolling moment and lateral characteristics resulting from the nonsymmetric roll angle of 26.6 deg are shown in Fig. 10. There are some differences between the predictions of programs MISSILE and MISSILE2 at the higher angle of attack and the agreement of both predictions with the test data is only fair. The program DEMON2 induced rolling moment predictions show agreement with the test data that is overall no better than the predictions of the other two programs.

Conclusions

Based on the results obtained in this study, the following conclusions have been derived:

1) Roll control at low angles of attack appears feasible on a Sidewinder-class missile by reducing the tail span.

2) Extrapolation outside the data base on which program MISSILE is based does not appear to be the reason for the bad rolling moment predictions reported by Blair and Rapp in Ref. 1.

3) Program MISSILE2 provides improved rolling moment predictions over program MISSILE, but further improvements appear needed.

4) Program DEMON2 provided excellent low-angle-of-attack rolling moment predictions and was superior to the other two programs at the higher angles of attack. The inclusion of afterbody vorticity should improve the general usefulness of this program.

5) Programs MISSILE and MISSILE2 provided very good predictions of longitudinal characteristics and fairly good predictions of lateral characteristics and induced effects.

References

[1] Blair, A.B. Jr. and Rapp, G.H., "Experimental and Analytical Comparisons of Aerodynamic Characteristics of a Forward-Control Missile," AIAA Paper 80-0374, Jan. 1980.

[2] Smith, C.A. and Nielsen, J.N., "Predictions of Aerodynamic Characteristics of Cruciform Missiles to High Angles of Attack Utilizing a Distributed Vortex Wake," Nielsen Engineering and Research, Inc., Mountain View, Calif., Rept. NEAR TR 208, Jan. 1980.

[3] Dillenius, M.F.E. and Nielsen, J.N., "Computer Programs for Calculating Pressure Distributions Including Vortex Effects on Supersonic Monoplane or Cruciform Wing-Body-Tail Combinations With Round or Elliptical Bodies," NASA CR-3122, April 1979.

[4] Schaefer, W.T. Jr., "Characteristics of Major Active Wind Tunnels at the Langley Research Center," NASA TM X-1130, July 1965.

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