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Aerodynamic Characteristics of a Canard-Controlled Missile at High Angles of Attack

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A low-speed wind-tunnel investigation was conducted to examine the aerodynamic characteristics of a one-third-scale model of a canard-controlled missile at high angles of attack using force and moment measurements. The data were taken at a nominal Mach number of 0.2 for angles of attack up to 50 deg at three different canard deflection settings. The test runs were limited to 0- and 45-deg missile roll angles (symmetric configurations) and two sets of tails (aft fins), one with the full area including the roll damping tabs (rollerons) and the other without the rollerons. The data indicate that the rollerons act as an effective fin area at low speeds and high angles of attack, and make the missile more stable. The test data were also used to validate the aerodynamic characteristics of the missile as predicted by the Missile Datcom program. The agreement between the Datcom predictions and the test data is fairly good, with the latter indicating a slightly higher static stability.

Nomenclature

A	= axial force, lb
AOA	= angle of attack, deg
C_A	= axial force coefficient, $A/q_\infty S$
C_m	= pitching moment coefficient, $M/q_\infty Sc$
C_N	= normal force coefficient, $N/q_\infty S$
c	= reference length (body diameter), in.
D	= model body diameter, in.
FW	= full tail (with rolleron)
M	= pitching moment, lb · in.
N	= normal force, lb.
NR	= tail without rolleron tab area
q_∞	= freestream dynamic pressure, $\frac{1}{2}\rho_\infty V_\infty^2$, lb/ft^2
Re	= freestream Reynolds number, $\rho_\infty V_\infty D/\mu_\infty$
S	= reference area, $\pi D^2/4$, in.^{2}
V_∞	= freestream velocity, ft/s
α	= angle of attack, deg
β	= angle of sideslip, deg
δ	= canard deflection angle (positive leading edge up, two fins deflected at $\phi = 0$, four fins deflected at $\phi = 45$ deg), deg
μ_∞	= freestream air viscosity, lb · s/ft^2
ρ_∞	= freestream air density, lb/ft^3
ϕ	= roll angle, deg

Introduction

FUTURE missile designs call for high-angle of attack (AOA) launching capability and better controllability to fully utilize the handling qualities of future combat aircraft. Expanding the maneuvering-envelope boundaries of a tactical aircraft to include controlled flight in the low-speed, high-AOA regime is a primary concern of today's aircraft designers. Studies have shown that the ability to perform rapid, transient maneuvers, even into poststall flight, can greatly enhance an aircraft's air combat capability and significantly improve mission success. The new generation of combat aircraft are therefore expected to have the capability to maintain controlled flight at low speeds and very high AOAs. This capability would allow the pilot to point the nose of his airplane and shoot a missile at a target well off the flight path of the airplane, thus launching a missile at a large AOA compared to traditional launches at AOAs of no more than 10 to 15 deg. The flight regime of low speed and high AOA has therefore aroused considerable interest among the missile community. A better understanding of missile aerodynamics at high AOAs is required in order to achieve an expanded missile launch window and to develop appropriate models for future design of missiles.

The high-AOA characteristics of a missile are highly configuration-dependent and vortex-dominated. The phenomenon of vortex breakdown (burst) and the onset of vortex asymmetry severely limit the high-AOA flight. The asymmetric vortex flow behavior has been documented in the literature for slender nose bodies at high AOAs.[1] This flow leads to unpredictable side forces, posing a potential threat to flight stability.[2–4] The so-called vortex-switching phenomenon, in which the vortex pattern rapidly switches from an almost symmetric configuration to a highly asymmetric one, has also been observed under certain flow condition.[5–7] The vortical flowfield around a missile at high AOA is thus very complicated; therefore the prediction of the aerodynamic characteristics is a challenging task. Current methods available for the prediction of missile characteristics include CFD codes and Missile Datcom. Most current aerodynamic computer codes are based on panel methods and therefore are restricted to small AOAs. The Missile Datcom program has been in use since the mid 1980s to predict aerodynamic characteristics of conventional missiles[8,9]; the latest version was released in 1993. The Datcom predictions at high AOAs, however, need experimental verification.

The aerodynamic data available on the behavior of missiles launched at high AOA are limited. Current missiles are designed to be aerodynamically stable, which leads to some flight conditions in which the missile cannot be launched without "tipping off" or "weathercocking." A better understanding of the missile aerodynamics and of the tipoff behavior at high AOAs is therefore highly desirable. Future missiles are likely to be designed marginally stable or unstable. Another issue for Sidewinder-type missiles is the lift of the roll dampers. The actual missile in flight will be stabilized by air-driven gyro wheels mounted in tail-fin hinged tabs, known as rollerons. At low speeds, the gyro wheels may not be

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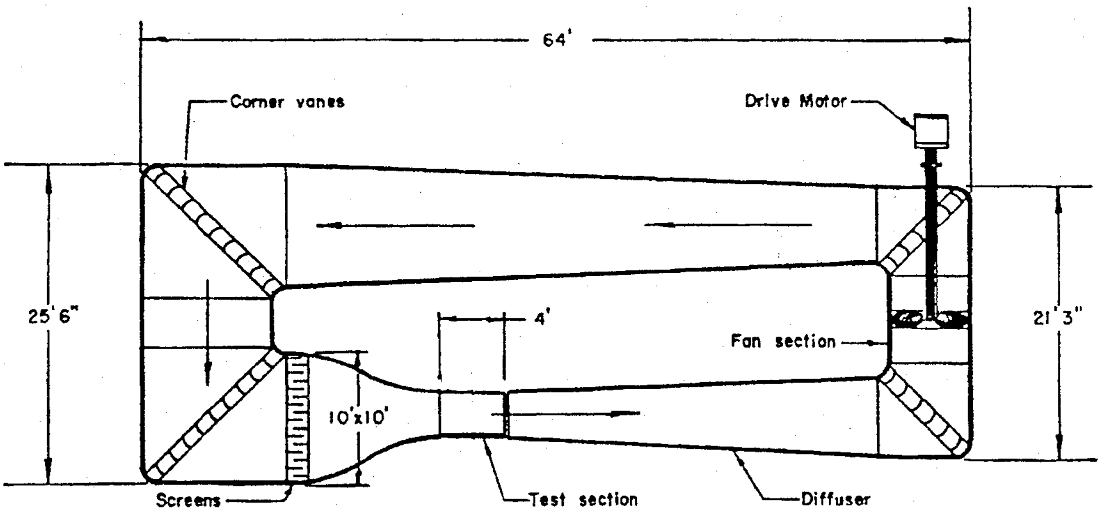


Fig. 1 Schematic layout of the NPS wind tunnel.

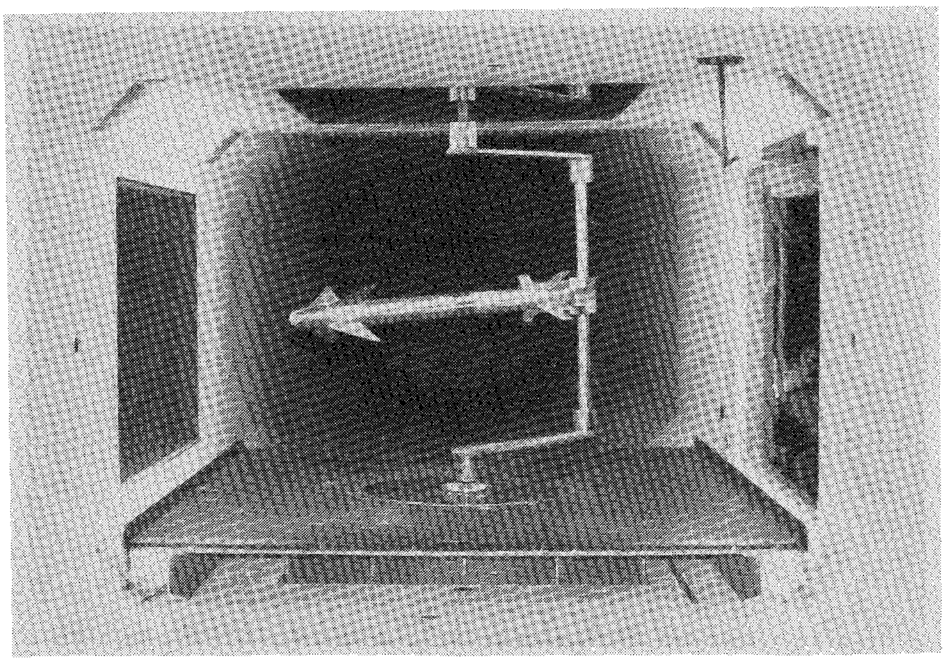


Fig. 2 One-third-scale missile model sting-mounted in the test section of the NPS wind tunnel (view from the settling chamber).

spinning fast enough to stabilize the tab, so there is some question as to whether this rolleron area is actually effective fin area. Current design capabilities for new missile configurations rely upon past experience with existing designs, prediction methods (using Datcom), and wind-tunnel experiments related to overall force and moment coefficients.

The advanced missile-airframe flight demonstration program of the Naval Air Warfare Center Weapons Division, China Lake, has flight-tested several design candidates as follow-on to the Sidewinder missile. The present investigation was undertaken in support of this program to provide aerodynamic data for experimental validation of models used in missile flight simulations, in particular the pitching moment data for use in stability analyses. In view of the question of rolleron lift, data were desired for tail fins with and without this rolleron area included. The investigation was conducted in the low-speed wind tunnel of the Naval Postgraduate School (NPS), to experimentally establish the low-speed aerodynamic characteristics of a canard-controlled missile model at high AOAs. Tests were conducted with two tail configurations, one representing the full tail with rolleron tab area and the other with the rolleron tab area removed. Six-component force and moment data were obtained at 0- and 45-deg roll angles and three canard deflection angles—0, +20, and −20 deg. All of the data were taken at a nominal Mach number of 0.2 and a nominal Reynolds number of 2×10^5 (based on the model body diameter). It should be emphasized that one of the intents of this investigation was to obtain high-AOA data on a future missile configuration for validating Datcom prediction. Additional details of the investigation appear in Ref. 10.

Table 1 Balance characteristics

Parameter	Full-scale load
Normal force	200 lb
Axial force	30 lb
Side force	100 lb
Pitching moment	300 lb·in.
Rolling moment	100 lb·in.
Yawing moment	150 lb·in.

Test Facility

The NPS low-speed wind-tunnel facility, shown in Fig. 1, has a 45- by 32-in. rectangular test section, a contraction ratio of 10:1, and a nominal freestream turbulence level of 0.2%. The test-section walls diverge slightly in order to avoid contraction effects caused by boundary-layer growth along the walls. It is a closed circuit,

Table 2 Model orientation, canard settings, and tail area for test runs

Run	ϕ, deg	β, deg	α, deg	δ, deg	Tail area
1	0	0	0–50	0	NR
2	0	0	0–50	20	NR
3	0	0	0–50	−20	NR
4	0	0	0–50	0	FW
5	0	0	0–50	20	FW
6	0	0	0–50	−20	FW
7	45	0	0–50	0	FW
8[a]	45	0	0–50	0	FW
9	45	0	0–50	20	FW
10	45	0	0–50	−20	FW
11	45	0	0–50	0	NR
12	45	0	0–50	20	NR
13	45	0	0–50	−20	NR

[a]Rerun to check on data repeatability.[10]

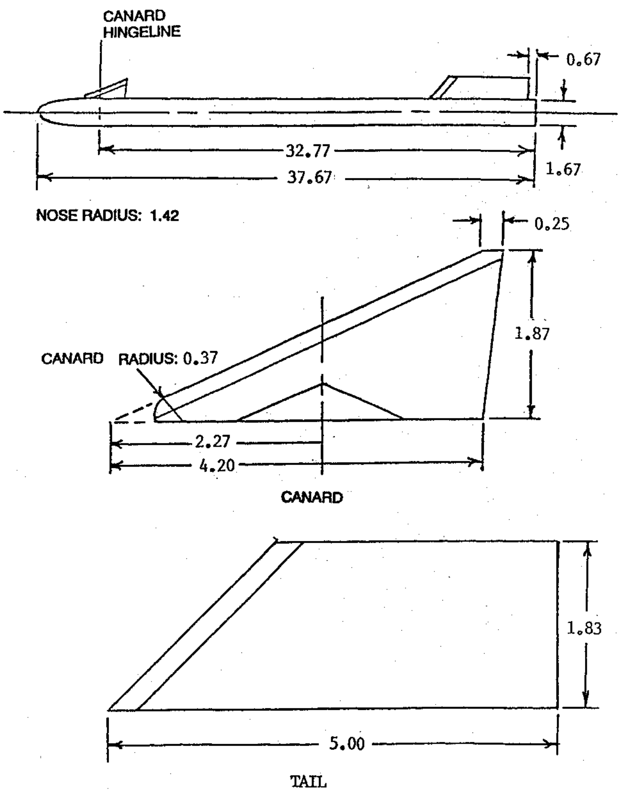


Fig. 3 Missile model configuration with full tails.

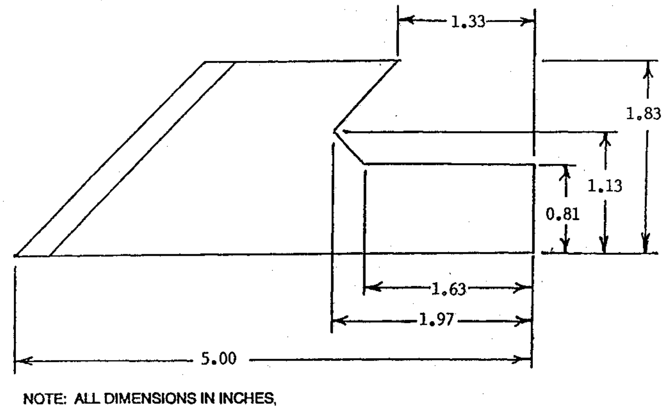


Fig. 4 Tail planform with rolleron area removed.

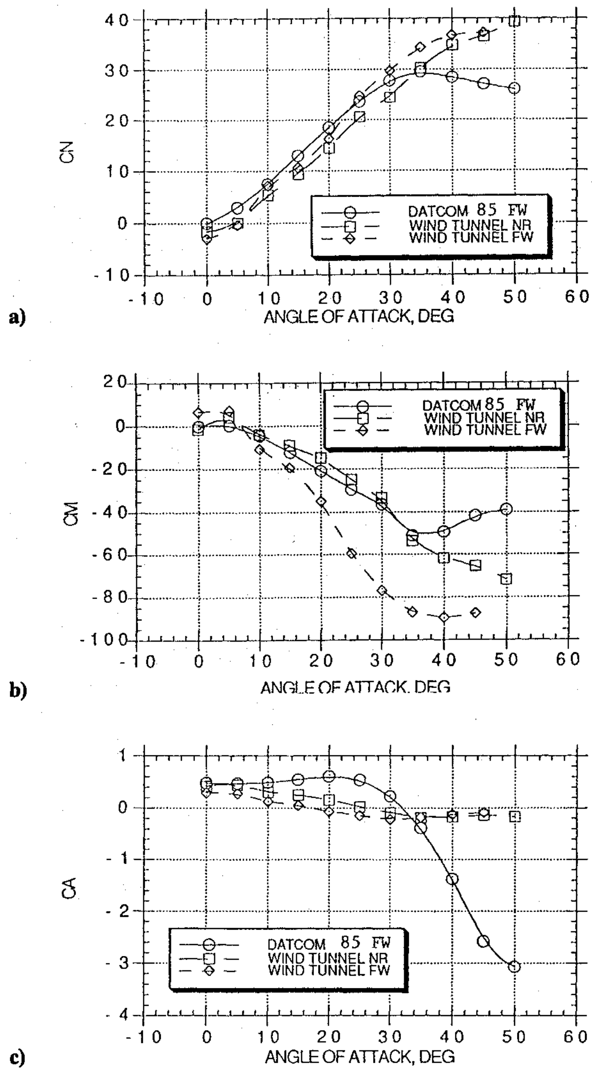


Fig. 5 Force and moment data for 0-deg roll angle ($\delta = 0$ deg).

continuous-flow wind tunnel with a maximum test-section flow velocity of 160 kt. The wind tunnel is powered by a 100-hp electric motor, which drives a three-bladed variable-pitch fan via a four-speed transmission. The test section is vented to the atmosphere at its downstream end; therefore the test section is at essentially ambient pressure. The wind tunnel does not have a cooling system; however, the internal air temperature did not exceed 90°F during the runs. A remotely controlled horizontal turntable mounted in the floor of the test section was used to vary the missile AOA. The model support system was designed so that the model center remained on the wind-tunnel centerline as the AOA was varied (Fig. 2). The geometry allowed AOAs up to 90 deg, but data were not taken beyond 50 deg because the clearance between the model and wind-tunnel walls would have been too small. At a 90-deg AOA, the nose would have been only 4 in. from the wall, which was considered unacceptable from the viewpoint of wall effects on the data. More details of the test facility may be found in Ref. 11.

Model and Instrumentation

The missile model used in the present investigations is a one-third-scale model of a canard-controlled missile configuration that was one of a series of candidates being proposed as a follow-on to the Sidewinder missile (Figs. 3 and 4). The model was of conventional metal construction and was fabricated by Micro-Craft, Hampton, Virginia. It was sting-mounted on a 0.75-in.-diam, six-component strain-gauge-type precision balance (on loan from NASA Ames Research Center) made by Task Corporation. The balance measured normal, axial, and side forces along with pitching, rolling, and yawing moments. In this paper, however, only normal and axial

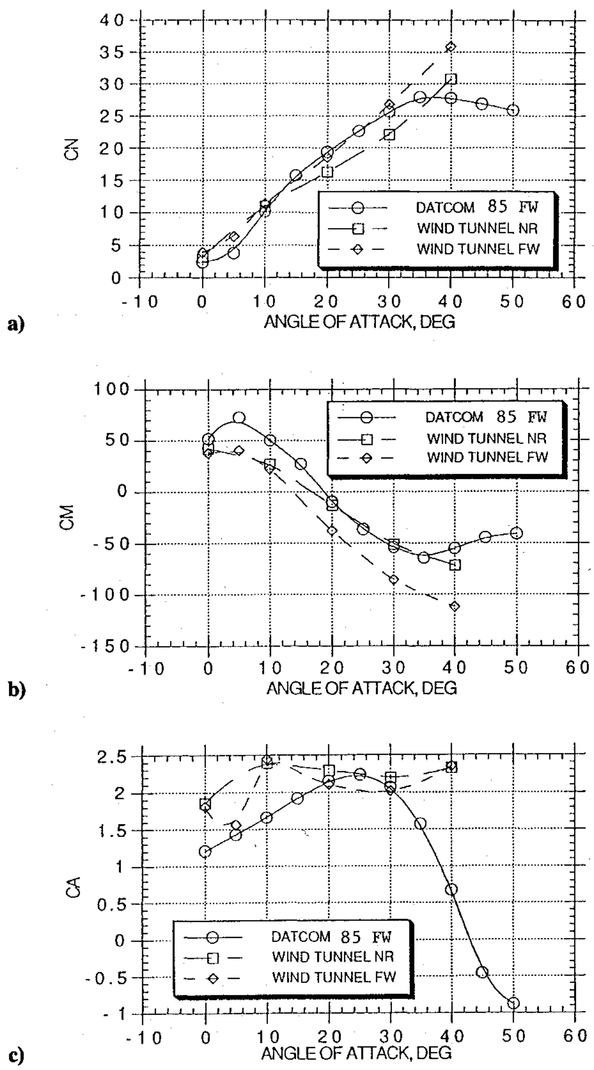


Fig. 6 Force and moment data for 0-deg roll angle ($\delta = 20$ deg).

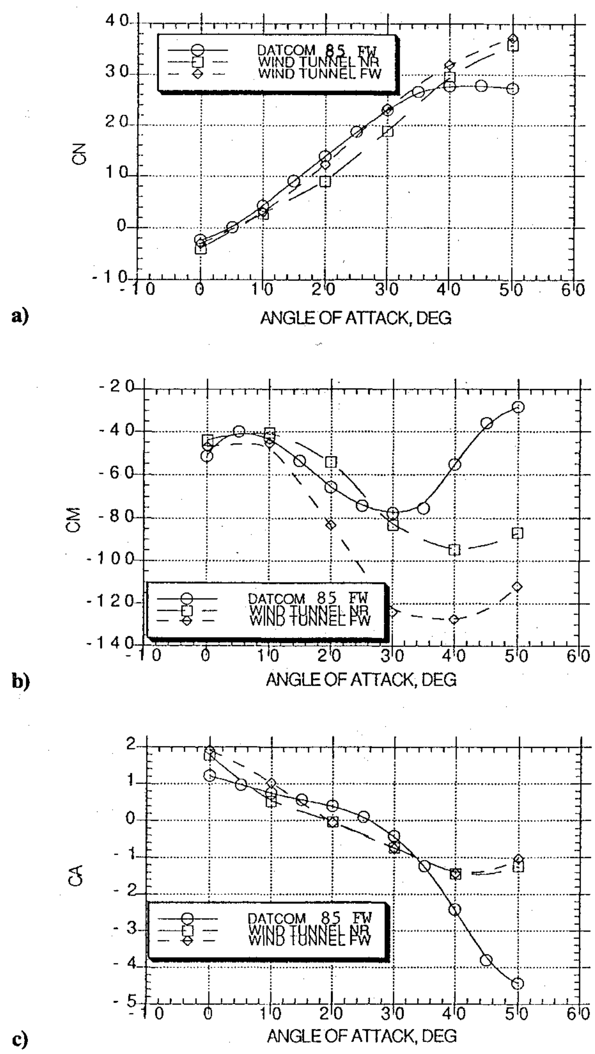


Fig. 7 Force and moment data for 0-deg roll angle ($\delta = -20$ deg).

force and pitching moment data are presented. Table 1 lists the load rating of the balance. The forces and moments are presented for a reference center located 18.487 in. from the model base for all configurations tested. In terms of the full-size missile this is equivalent to a center-of-gravity location 57.5 in. aft of the nose. Both the reference length (1.667 in.) and the reference area (2.1816 in.^{2}) used in the data reduction are based on the model body diameter.

The model was fitted with boundary-layer transition strips located 1.20 in. aft of the body nose and 0.40 in. aft of the canard and tail-fin leading edges (measured streamwise). The transition strips were made of no. 50 grit embedded in acrylic plastic and were 0.062 in. wide. Accurate determination of the zero-lift drag during the test was not contemplated, as this would have required a much more detailed and costly model; therefore, no attempt was made to simulate launch lugs and other minor details. The model was fitted with pressure taps to measure the balance cavity pressure; however, these were not used during the tests. Hence, the axial force data presented in this paper include the base drag due to whatever cavity pressure existed.

The data acquisition system used in conjunction with the strain-gauge balance consisted of a signal conditioner, a relay multiplexer, an amplifier, a digital multimeter, and a microcomputer (see Ref. 11 for more details). The computer output presented the balance loads in engineering units. These data were subsequently put into an Excel spreadsheet on a Macintosh portable computer and reduced to coefficient form.

Test Conditions

All test runs were made at a nominal Mach number of 0.2 and a nominal Reynolds number of 2×10^5 (based on the model diameter), which corresponded to a dynamic pressure of 59 lb/ft^2 at a tunnel freestream velocity of 225 ft/s. The force and moment data were obtained at 5-deg intervals in the 0- to 50-deg AOA range at 0- and 45-deg roll angles. Tests covered three canard deflection-angle settings and two tail configurations, one representing the full tail (with rollerons) and the other without rollerons. Table 2 lists the test matrix showing model orientation, canard settings, and tail area for different test runs. Run 8 was a rerun intended as a check on data repeatability between wind-tunnel entries.[10]

Results and Discussion

The results of the investigation are presented and discussed in this section. The reduced data, which are presented in plot format (Figs. 5–12), include the normal force coefficient C_N, the pitching moment coefficient C_M, and the axial force coefficient C_A. The side force coefficient, the yawing moment coefficient, and the rolling moment coefficient are not shown, as all of the test runs were conducted with symmetric configurations at zero yaw angle, and consequently the corresponding forces and moments were expected to be relatively small. The sign convention adopted for the forces and moments was standard, with normal force positive upward, axial force positive rearward, and pitching moment positive nose up. Factors beyond experimental control, such as slight voltage fluctuations in the power supply (which in turn caused drift and variation in the measurements of forces and moments) and the inability to establish exact pitch attitudes, led to some variation in the data from run to run. Reference 10 discusses the results of a rerun test intended as a check on the repeatability of balance data. The data repeatability was found to be good in the case of normal force data but only fair for the pitching moment and the axial force data.

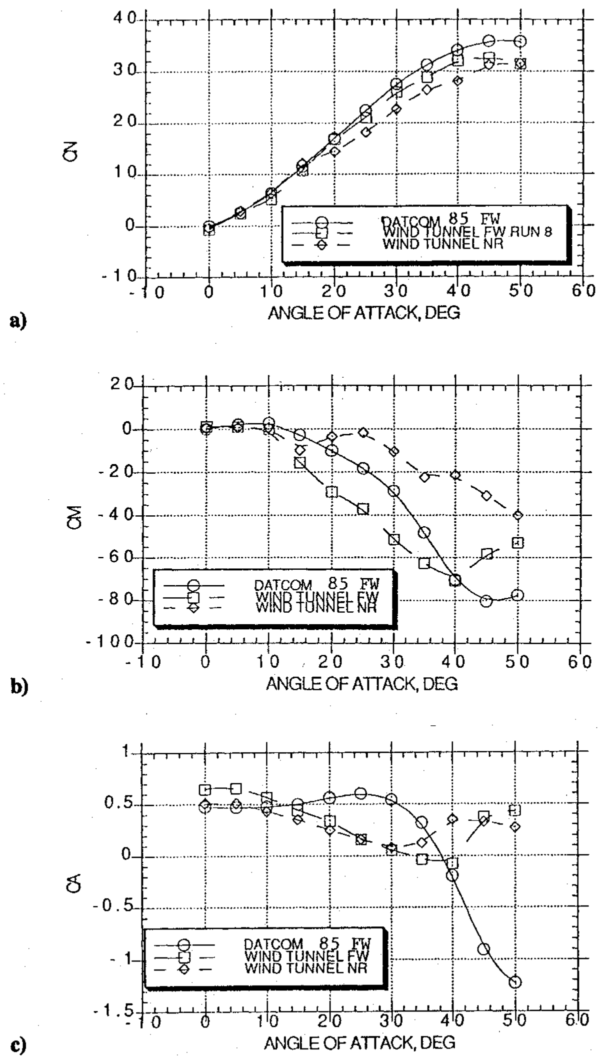


Fig. 8 Force and moment data for 45-deg roll angle ($\delta = 0$ deg).

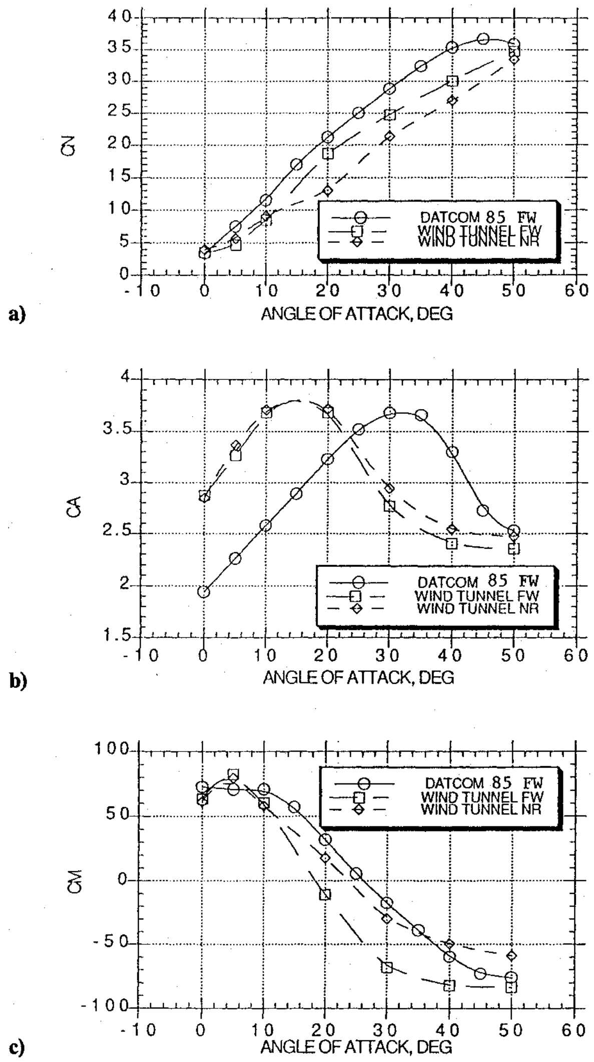


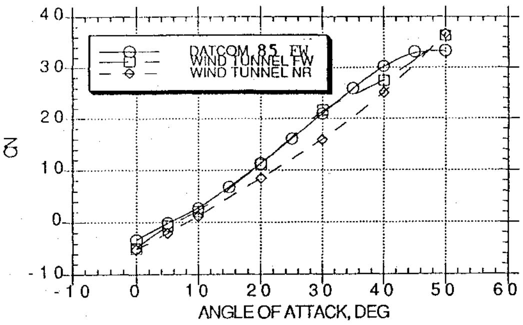
Fig. 9 Force and moment data for 45-deg roll angle ($\delta = 20$ deg).

Figures 5–7 show results for 0-deg roll angle (i.e., + configuration) as a function of AOA for canard deflections of 0, 20, and −20 deg, respectively. Two sets of data are shown here, one corresponding to the full tail with the rollerons included (denoted as FW) and the other without rollerons (denoted as NR). Also shown for comparison are the results predicted by the 1985 version of Missile Datcom[8] for the FW case. Both sets of the data show a monotonic increase of C_N with AOA (Figs. 5a, 6a, and 7a), but a close examination of the data indicates a slight increase in C_N for the full-tail case, particularly at high AOAs, as would be expected. The agreement between these data and the prediction is good up to about 35-deg AOA, after which the prediction shows a decrease in C_N. The C_m data in Figs. 5b, 6b, and 7b indicate greater negative slope of the moment coefficient curve for the full-tail case. Thus, the missile becomes less stable without the rolleron area. Compared with the experimental data, the Datcom prediction gives the same trend as the test results, but the discrepancy between the data and the prediction widens at high AOAs. The Datcom prediction yields minimum C_m at about 35-deg AOA. In the case of the axial force data (Figs. 5c, 6c, and 7c), the Datcom prediction deviates from the data appreciably for AOAs > 35 deg. Note that in this range, Missile Datcom predicts large negative axial forces and the difference between the two sets of test data is minimal.

The effects of canard deflection-angle settings can also be seen in these figures by comparing the respective plots for canard deflection with those for 0-deg canard deflection. The 20-deg positive canard deflection gives a large nose-up pitching moment. The pitching moment becomes zero at about 16 deg for the NR configuration, and about 14 deg for the FW configuration. Hence, the maximum missile trimmed AOA is 16 deg for the NR case and 14 deg for the full-tail case. It is interesting to note that the 20-deg nose-up case actually produced less nose-up pitching moment at 40-deg AOA than did the zero-degree case. The reason for this is that the canard is fully stalled, which causes a loss of lift and hence less nose-up moment. The loss of lift is seen in the NR case, but the FW data show about the same normal force coefficient at 40-deg AOA. The 20-deg negative deflection gives a large nose-down pitching moment, as expected. The difference between the Missile Datcom prediction and the test data is especially large at the higher AOAs, as can be seen in Fig. 7b.

Figures 8–10 show the experimental data for 45-deg roll angle (i.e., × configuration) as a function of AOA for canard deflections of 0, 20, and −20 deg, respectively. As in the previous figures, two sets of data are shown here (denoted by FW and NR) along with the prediction by the 1985 version of Missile Datcom[8] for the FW case. A comparison of these plots with those for the 0-deg roll angle (i.e, + configuration of the model) shown in Figs. 5–7 shows that the general trend of the data for the × configuration follows closely that for the + configuration, although there are some minor differences. Again, the experimental data show greater stability than the Missile Datcom prediction.

The predictions of the 1985 and 1991 versions of the Missile Datcom[8,9] for the FW case with zero canard deflection are compared with the experimental data for 0- and 45-deg roll angles in Figs. 11 and 12, respectively. As can be seen in these figures, the difference between the two predictions increases with AOA and becomes substantial at high AOAs (> 40 deg). The prediction of the 1991 version of the Missile Datcom does not show any obvious improvement in agreement with the experimental data. For the pitching



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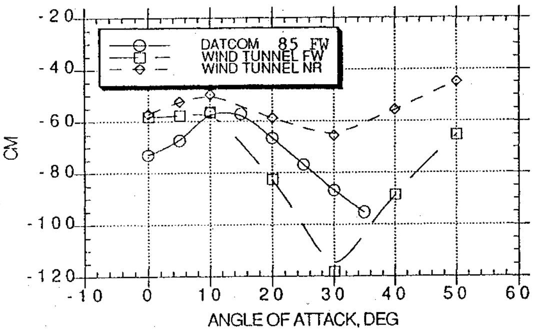

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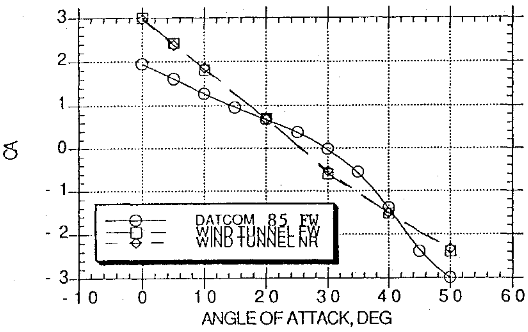
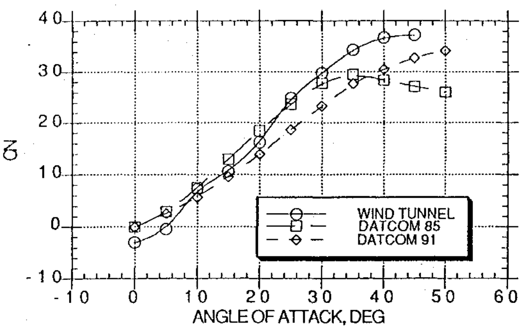


c)

Fig. 10 Force and moment data for 45-deg roll angle ($\delta = -20$ deg).



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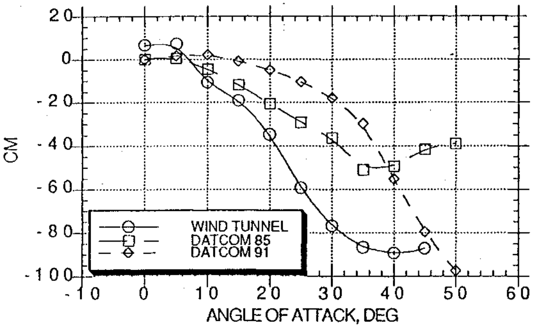
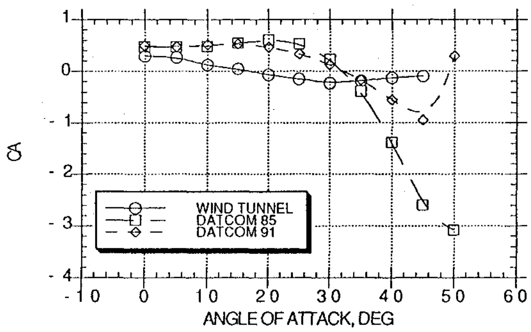


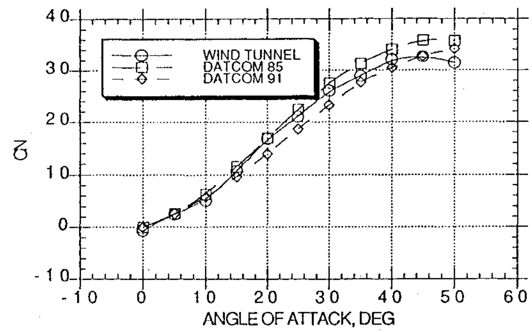
b)

Fig. 11 Comparison of missile Datcom predictions with the experimental data for the full-tail configuration (FW) at 0-deg roll angle ($\delta = 0$ deg).



c)

Fig. 11 (Continued) Comparison of missile Datcom predictions with the experimental data for the full-tail configuration (FW) at 0-deg roll angle ($\delta = 0$ deg).



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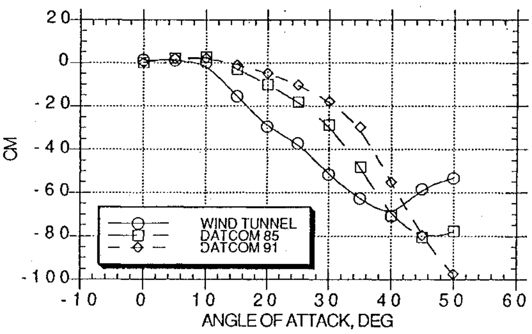

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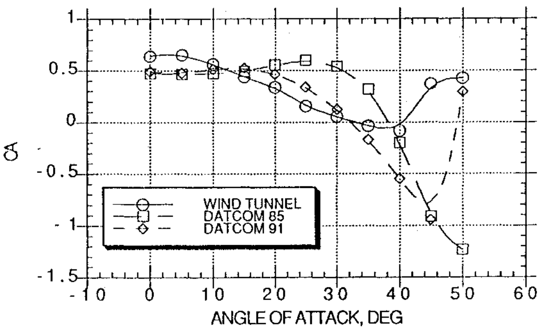

c)

Fig. 12 Comparison of missile Datcom predictions with the experimental data for the full-tail configuration (FW) at 45-deg roll angle ($\delta = 0$ deg).

moment the 1985 version predicts closer to the data, whereas for the axial force the 1991 version gives better agreement. Either version of the Missile Datcom predicts the data reasonably well for the normal force.

Conclusions

A low-speed force and moment wind-tunnel investigation was conducted on a one-third-scale model of a canard-controlled missile to examine the high-AOA aerodynamic characteristics. Force and moment data were obtained in the 0–50-deg AOA range for + and × configurations of the model at three different canard deflection-angle settings and tail areas, with and without rollerons. The data also served as a standard to check the predictions of both 1985 and 1991 versions of the Missile Datcom. The following conclusions are drawn from the results of the investigation:

1) The missile is about neutrally stable at AOAs below 10 deg, but shows positive static stability at higher AOAs. It is less stable, however, when the rolleron tab area is removed.

2) The normal force data indicate slightly reduced lift with the rolleron area removed.

3) The data show a maximum trimmed missile AOA of 16 deg for the NR configuration and 14 deg for the FW configuration.

4) The general trend of the data for + and × configurations is similar.

5) Although there is appreciable difference between the two missile Datcom predictions, neither can claim to predict the data better.

6) The agreement between the experimental data and the missile Datcom predictions is fairly good, with the data showing greater stability.

Acknowledgments

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