AIAA 81-0007R

Influence of Support Systems on the Aerodynamics of an Inclined Ogive Cylinder

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The influence of the model support system on an ogive cylinder at high angles of attack has been determined in subsonic and transonic tests. Stings of varying diameter and struts in various orientations were studied. The stings did not alter the development of large side loads resulting from asymmetric vortex separation and had only moderate progressive effects on in-plane forces and moments. Struts supporting the model through its leeward meridian seriously altered normal and side forces and sharply reduced base drag at several combinations of Mach number and angle of attack. A strut supporting the model at its windward meridian (near the base) yielded results like those for the stings.

Nomenclature

C_{D_B}	$= (P_\infty - P_B)/q_\infty \pi D^2/4)$
C_N	= normal force/ $(D^2/4)$
C_Y	= side force/$(q_\infty \pi D^2/4)$
D	= diameter of cylindrical fuselage
d	= diameter of sting
M	= Mach number
P_B	= pressure acting on exterior face of model base-closure plate
P_∞	= freestream static pressure
X_{CP_N}	= distance from ogive apex to center of pressure of normal force/D
X_{CP_Y}	= distance from ogive apex to center of pressure of side force/D
α	= angle of attack

Introduction

THE need for guided missiles and aircraft to undergo high accelerations results in the requirement for flight at high angles of attack. In order to design the vehicles and their control systems it is necessary to know what aerodynamic forces and moments act on the body. Tests in wind tunnels to provide the needed information usually involve conventional supports (sting or strut); the effects of these supports on the measurements must be known in order to interpret the test results. The support interference at small model incidence has been the subject of many experiments conducted in a wide range of environments for many configurations. Very little data exist even for simple bodies at very high incidence; and some of the tests indicate that rather large effects are introduced by supporting struts, particularly at subsonic and transonic speeds.[1,2]

The present test program investigates support interference for a body of revolution supported by stings and struts. Measurements were made to determine how support position, size, and shape affect the forces, moments, and base pressure acting on an ogive cylinder with a fineness ratio of 7.5. In particular the asymmetry of the flow and the corresponding side force and yawing moment acting on the body as affected by stings of various size and struts having different positions and sweep angles were studied.

Wind Tunnel and Test Configurations

Wind Tunnel

The Ames 14 ft transonic wind tunnel is a closed-return continuous-flow wind tunnel.[3] Its test section is enclosed in a plenum and has slotted walls to reduce interference with the model flow at transonic speeds. The stagnation pressure is atmospheric because temperature control is effected by passive air exchange with the exterior atmosphere.

Model

The model for the present study was a 17.8 cm diam (D) tangent-ogive cylinder of fineness ratio 7.5. The ogive was sharp and had a fineness ratio of 2 (see Fig. 1).

The model was mounted on the internal force and moment strain gage balance in such a fashion as to permit remote adjustment of the roll position at any time during the test without consideration of Mach number or angle of attack.

Model surface finish, which has been found to be critical in earlier basic investigations of the phenomena of asymmetric vortex separation, was not controllable during this investigation. The interior of the Ames wind tunnel is subject to continuing flaking of paint. Furthermore, dust from outside the tunnel may gain access through the air exchanger in the return path. The resulting sandblasting is so rapid that a short operating sequence started with a perfect surface would end with a large number of craters, some with burrs as high as 0.1 mm. It was therefore decided that only the most severe burrs would be removed between tests so as to have a quite rough surface to start the test of each configuration and to minimize the change in overall roughness during the tests of that configuration. In an effort to provide a single feature which would predominate over the sandblasting burrs in controlling the flow asymmetries, the model was equipped with a trigger near the apex. This trigger was a ridge of epoxy glue approximately 0.4 mm thick by 1.5 mm wide which extended about 18 mm along one generator of the ogive starting 7.6 mm from the tip. The trigger was much larger than any of the burrs and was placed near the nose in order to achieve high effectiveness.

Sting and "High-Alpha" Strut

The model was mounted, by way of the balance, on a tapered steel sting which extended 5 model diameters from the model base to its mounting socket. Where the sting exited the model base, its diameter d was 76 mm. The socket was, in

Presented as Paper 81-0007 at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Mo., Jan. 12-15, 1981; submitted March 6, 1981; revision received Aug. 18, 1981.

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turn, installed on the end of a massive strut mounted at a 45 deg angle from the wind-tunnel main model-support body of revolution. The full range of angle of attack provided by this mounting arrangement extended from approximately 34 to slightly over 73 deg.

Dummy Stings

To investigate the incremental effect of enlarging the sting on the forces and moments experienced by the model, dummy stings on various diameters were mounted on the real sting (Fig. 1). Extrapolating any observed dependence on sting size to zero sting diameter would then give the "best" baseline data free of interference from the supports. The baseline used herein, however, is that obtained with the sting having $d/D=0.43$. Each dummy sting was a right circular cylinder 35.6 cm long and all dummies were sharply boattailed at the downstream end. All were mounted so as to provide a 6 mm ($0.04D$) gap between the forward end and the model base-closure plate.

Dummy Strut

The dummy strut (Fig. 2) was fabricated by laying up a fiberglass-reinforced plastic structure around a thin plank of oak. The resulting plank was 18 cm wide by 2.5 cm thick, and had rounded leading and trailing edges. This strut was suspended from auxiliary structures mounted on the model-support system.

Because it was necessary to move the dummy strut laterally during the tests to align its chord plane with the axis of the model, a compliant, rubber-cushioned mount was provided at the support end of the strut and two controllable 3 mm guy wires were fastened to a fitting which passed through the dummy strut near its tip. The active alignment was accurate to within about 6 mm.

Tests

The effects of supports on the observed aerodynamic characteristics were determined from comparison of data obtained using the various dummy supports with data obtained with the most slender sting without the dummy support systems or with the leeward support blade installed, as appropriate. The three types of tests described below were conducted to permit the required comparisons.

Baseline Tests

The baseline test configuration consisted of the ogive cylinder body (with epoxy asymmetry "trigger" in place) and the most slender sting. No dummy stings, dummy struts, or guy wires were installed for this test. Similarly, the test configuration for comparison with the leeward dummy strut configurations consisted of the same model and sting plus the leeward support blade.

Test Conditions

The freestream Reynolds numbers based on model diameter were 1.8×10^6 at $M=0.5$, 2.2×10^6 at $M=0.7$, and 2.4×10^6 at $M=0.9$. Angle of attack was varied from 34 to 73 deg. Nine roll positions (the last repeated the first) were set at each test condition (Mach number and angle of attack). Following each set of roll position settings at constant Mach number and angle of attack, the model was returned at roughly constant roll rate of 6 deg/s to the starting point. During this rollback the outputs of the main balance normal- and side-force gages were recorded continuously along with the model roll position for a complete revolution.

In the tests of the five configurations employing the dummy strut a gap as great as 25 mm separated the strut tip from the model in order to prevent mechanical interference under maximum loading. Two tests were terminated before the complete text matrix was recorded because of fouling.

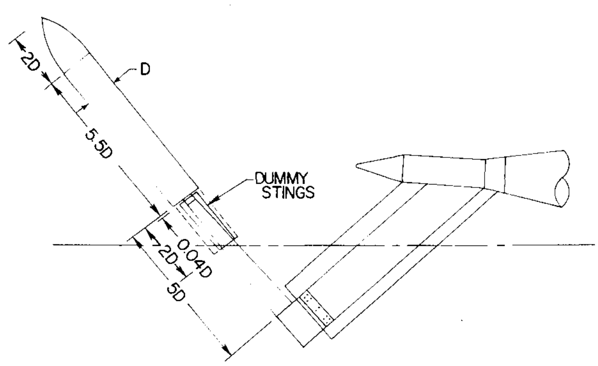

Fig. 1 Model and dummy stings.

Results and Discussion for Sting Supports

Normal Force

At each test condition the balance and base pressure data were recorded at eight different roll positions (twice at one roll position). The smallest of the observed values of normal-force coefficient for the thinnest sting are plotted as a function of angle of attack for the three Mach numbers in Fig. 3. As the sting diameter was increased, the observed minimum normal force increased barely perceptably at low angles of attack at the lower Mach numbers and more rapidly at the higher angles of attack. At $M=0.9$ only the largest sting caused a large increase at angles of attack below 59 deg. Selected data are shown in Fig. 4.

As will be described later, the model was subjected to large side loads despite its ostensibly symmetric geometry. The normal force was frequently observed to change system-

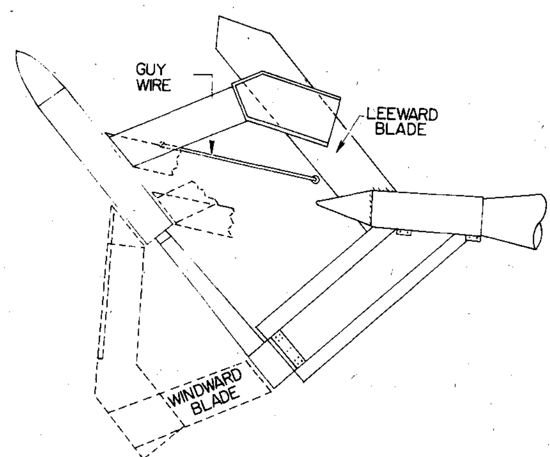

Fig. 2 Model and dummy strut.

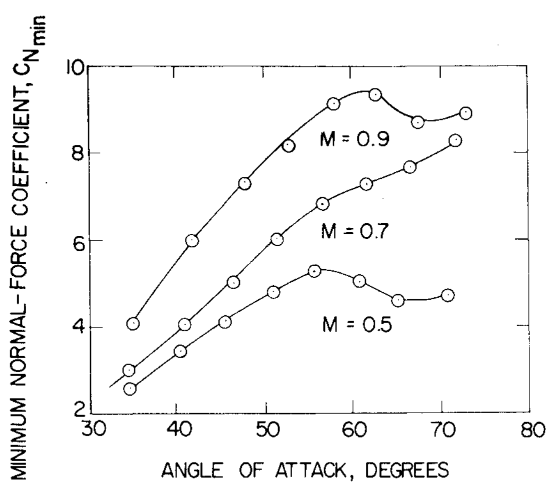

Fig. 3 Variation of minimum observed normal force with angle of attack (sting diameter = $0.43\times$ body diameter).

atically with side force. Examples of this variation are illustrated in Fig. 5. Increments in normal force ΔC_N as great as 30% or more above the minimum were observed when the model was simply rolled to eight different positions while holding a constant angle of attack. Since this wide range of normal force results solely from changes in roll position of an apparently axially symmetric model, it is important to recognize the effects of model flow asymmetry. In designing a support system it is important to avoid altering this apparently natural asymmetry and its effects on the aerodynamic loads.

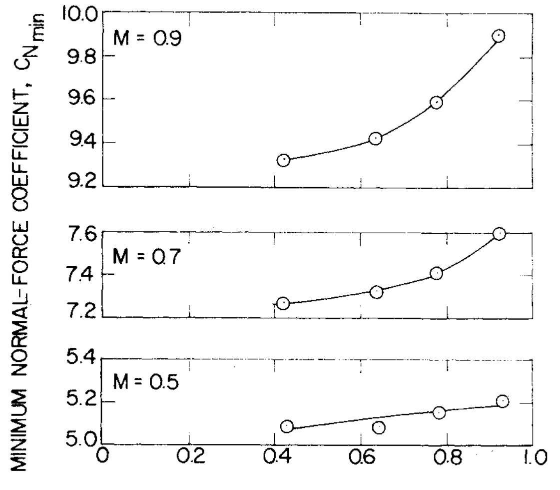

Fig. 4 Effect of sting diameter on minimum normal force ($\alpha \approx 62$ deg).

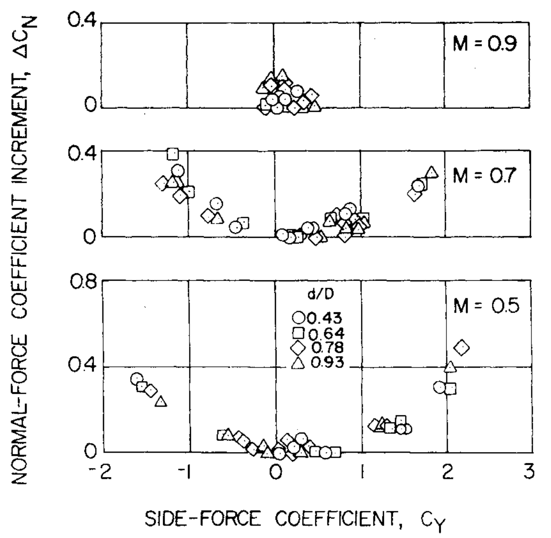

Fig. 5 Normal-force relationship to side force for four sting diameters at $\alpha \approx 41$ deg.

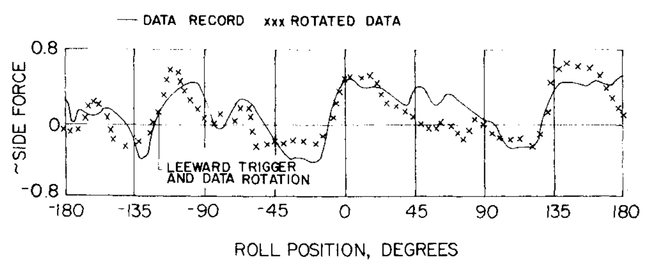

Fig. 6 Symmetry of side-force "signature" ($M = 0.5$, $\alpha = 50$ deg, $d/D = 0.64$).

The above data show a weak tendency toward increasing incremental normal force with increasing sting diameter at a given side force. This tendency is in addition to the stronger tendency toward increasing minimum normal force with increasing sting diameter (Fig. 4).

Side Force

The effect of asymmetric flow on side force is well illustrated in the continuous records of side force as a function of roll position for one combination of Mach number and angle of attack (Fig. 6). The irregular variations proved to be fairly repeatable in overall form, but changed in fine detail from run to run. These changes in detail make interpretation of the data difficult. No discernable trend in side-force "signature" with increasing sting diameter was observed.

The side-force variations with roll position are controlled by minor irregularities or asymmetries in model or airstream. Just which model asymmetries affect the results of a particular test is usually difficult or impossible to determine; in the present test a fixed asymmetry was provided in the form of the trigger applied to the model nose. This trigger was easily the largest asymmetry on the model nose. Had it been the only irregular feature capable of affecting the flow, the side-force data at those roll positions where the trigger was effective would be precisely antisymmetric about the roll positions at which the trigger passes through the windward or leeward meridian. To visualize this test of antisymmetry, consider the line plot in Fig. 6. If one cuts the plot in two at a postulated roll angle for antisymmetry (e.g., where the trigger passes through the leeward meridian) and then swings one piece of the plot through an angle of 180 deg about the point where the horizontal axis crosses the cut, the rotated plot will have a reversal in sign conventions for both roll position and side force. If the data curve is precisely antisymmetric the two sections will superpose perfectly; as antisymmetry degrades, the overlays will be degraded. This process was applied to the data of Fig. 6 (with an estimated allowance for an apparent bias toward positive side force) and the results are shown in the figure as a set of x's. The cut-and-rotate point to give the best overall overlay was at a roll position of about $\phi = -117$ deg; the roll angle at which the trigger passed through the leeward meridian was measured to be about -118 deg. The good match suggests that the trigger was the principal irregularity influencing the flow asymmetries in the vicinity of that roll position. In contrast to this suggestion of antisymmetry at $\phi \approx -117$ deg, the data in the region of $\phi = 63$ deg, when treated in the same way, show no evidence of antisymmetry. It is concluded that the trigger was quite ineffective when oriented within 30 deg of the windward meridian at $\alpha = 50$ deg.

Normal-Force Center of Pressure

As sting diameter is progressively increased, the center of pressure of the normal force acting on the model moves gradually aft. This effect is greatest at the lower Mach numbers and highest angle of attack. At Mach 0.7 and 72.2 deg angle of attack the center of pressure moves aft by about 24% of the body diameter when the largest dummy sting is installed over the baseline sting. This effect is greatly reduced for the highest Mach number, smaller stings, and smaller angles of attack. To put these trends into perspective, however, it is noted that at a given value of d/D the effect of flow asymmetry can be as much as three times that resulting from increasing sting diameter from $d/D = 0.43$ to 0.93.

Side-Force Center-of-Pressure Position

The movements of the center-of-pressure position of the side force were studied by comparing systematically, plots of side-force center of pressure and side-force amplitude vs roll position for the four sting diameters. A few general observations can be drawn from the study of those test pairs where the side force itself was fairly large, $|C_Y| > 0.75$. For angles of attack less than 50 deg, the center-of-pressure position of side force typically remained stationary ($\pm 0.15D$) for all sting diameters tested. At an angle of attack of 55 deg the side-force center of pressure appeared to move gradually forward by about 0.4 diam as the sting size was changed from smallest to largest.

Forebody Axial Force

Unlike all other aerodynamic properties of the model, the axial force exclusive of base drag varied only slightly as the model roll position was varied for the tests with the most slender sting; a tendency toward reduced axial force with increased side force was seen. The effect of sting diameter on axial force was not precisely established because of the incompletely defined pressure field in the gap between the dummy stings and the model's base closure. Therefore, the discussion here is limited to noting the systematic increase of base drag with increasing side force, shown in Fig. 7, for the thinnest sting and for the test with the leeward support blade in place (no strut). While even the most slender sting doubtless altered the base pressure from its support-free value, it is assumed that any increments resulting from inserting the strut would be the same whether the sting were present or not.

Results and Discussion for Strut Supports

Strut at Model Base

In general, the influence of the strut on the aerodynamic loads was very small for those cases where it intercepted the model near the base. It must be emphasized, however, that at high angles of attack the strut was immersed in the wake of the sting, or vice versa, so that the true influence of either, if used in the absence of the other, may not have been adequately determined. When the strut was placed to windward the shielding reduced the normal force acting just forward of the model base and moved the center of pressure only perceptibly forward. The windward strut had no noticeable effect on side loads. Typical normal-force results for the model with support blade and with support blade and leeward dummy strut (two sweep angles) are presented in Fig. 8. For the cases showing small side force there appears to be a small reduction in normal force when the dummy strut and its guy wires are added. At 60.8 deg angle of attack a moderate increase in side-force range occurred when the strut was installed in the aft position at a sweepback angle of 15 deg. It is believed that for the baseline case the small side force resulted from offsetting side loads fore and aft; installation of the strut, by reducing the aft side load, would then result in a net side-load increase. The side-load center of pressure for these cases was located near the nose-cylinder juncture for the strut-on configuration (about 4 diam forward of the strut). There appears to be a slightly more serious effect on the normal force for highly asymmetric cases (large side force). At $\alpha = 50.7$ deg and $M = 0.5$ a maximum change of 10% is evident. No effect of strut sweepback angle is apparent at $\alpha \leq 50.7$ deg.

The introduction of the aft-mounted strut caused only small changes in normal-force center-of-pressure position at all angles of attack except 50.7 deg at $M = 0.5$ for the leeward case. Here the shift was typically 0.1-0.2 of the body diameter throughout the side-load range as shown in Fig. 9.

The aft strut did not alter the axial force acting on the forebody. When mounted to windward, the strut also had no effect on base drag. The effect of the leeward strut on base pressure is described in the next section.

Leeward Strut Mounted at Midcylinder Position

This configuration is different from the other strut cases principally in that the strut's effects on the wake of the model can be felt for a substantial distance aft of the strut itself. When the dummy strut was placed leeward of the model at midcylinder, it reduced the range of side loads felt at moderate angles of attack and reduced the normal force at the highest angles of attack (see Fig. 10). The reduction was most severe at $\alpha = 51$ deg for both $M = 0.5$ and 0.7. As might be expected, the drastic reduction in side force also resulted in a large forward shift in side-force center-of-pressure position when the side force was large. This result is illustrated for $M = 0.5$ and $\alpha = 40.5$ deg in Fig. 11.

Where the baseline configuration showed large side force, the strut canceled much of the after part of the load so that the center of pressure moved forward by about 1.4 diam; at small side load the strut had little effect. It is considered probable that the modest flow asymmetry in this latter case developed aft of the strut so that the strut could not experience side loads and generate canceling vortices.

At the highest angle of attack at $M = 0.7$, the normal force was reduced by about 11% when the strut was installed at midcylinder. This loss is believed to be analogous to the reduction of drag acting on a right circular cylinder in two-dimensional flow resulting from installation of a splitter plate in the wake.[4,5] The oil flow pictures in Fig. 8 of Ref. 6 show that the surface streamlines on the lee side of an ogive cylinder model at 90 deg angle of attack are drastically rearranged by introduction of the dummy strut. A similarly drastic reduction of normal force accompanies this change in configuration. Since the present strut can affect the body's wake flow both forward and aft of its own position, it is potentially more influential than it would be if placed near the model base. In the latter case the reduction in normal force was only about 5%. The influence was found to be much weaker at smaller incidence and at $M = 0.5$ even at the highest angle of attack. Operation of this configuration at $M = 0.9$ resulted in violent vibration of the strut, so no data were obtained at incidence above 42 deg.

In addition to the drastic effects on the forebody loads, the leeward dummy strut at midcylinder altered the base drag substantially. The key effects are illustrated in Fig. 12. Similar changes were found for the aft installation of the leeward strut. When placed to leeward the strut can affect the base

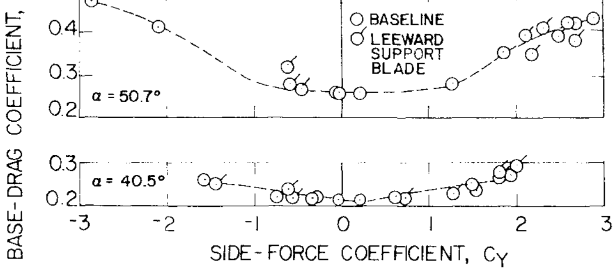

Fig. 7 Relationship between base drag and side force ($M = 0.5$).

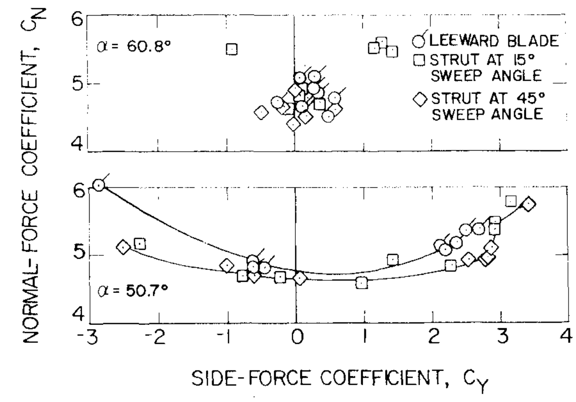

Fig. 8 Effect of leeward aft strut on normal force ($M = 0.5$).

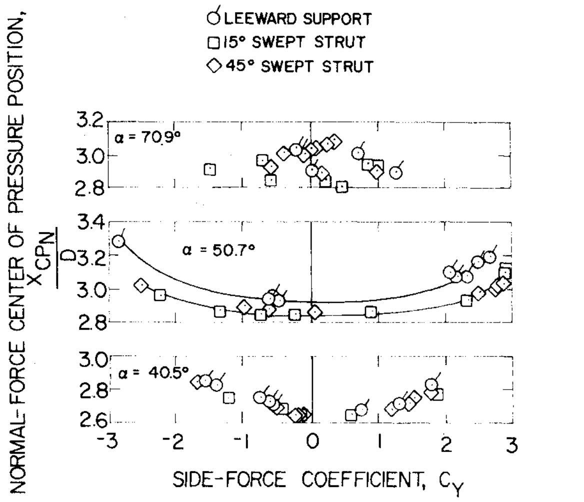

Fig. 9 Effect of leeward aft strut on center of pressure of normal force ($M = 0.5$).

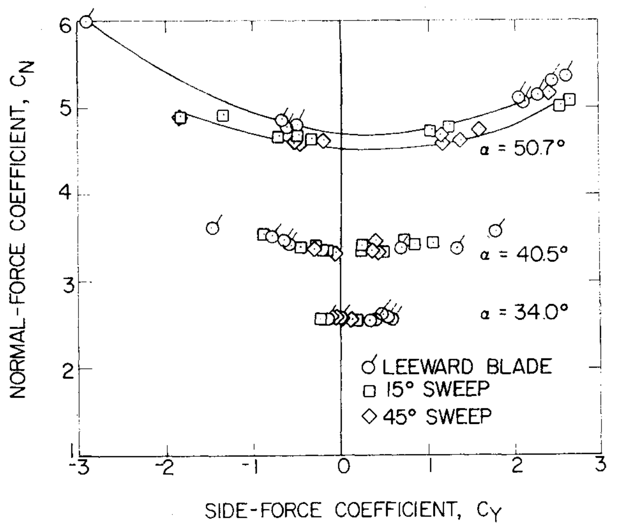

Fig. 10 Effect of leeward strut at midcylinder on normal and side forces ($M = 0.5$).

pressure through two mechanisms: 1) the thickness distribution of the strut can produce a change of static pressure in its wake and thus alter the base pressure and; 2) the strut can alter the strength of vortices passing near it by introducing the reaction vortices induced by the lift distribution arising from the incident body vortices. The new resulting vortices will tend to oppose the initial set. In view of the large variation of base drag with side force acting on the baseline configuration, it is felt that the vortex influence is very strong and that the leeward strut in fact suppressed the vortex strength near the model base. The thickness-induced effects of the strut should be present in both windward and leeward cases; since only the leeward strut affected the base drag it is concluded that the vortex cancellation mechanism is the important factor.

The far-reaching effects of the strut, when mounted in the leeward flow of the model make this the poorest model support configuration of those tested.

Conclusions

The present study of support interference on an ogive cylinder at high angles of attack has led to the conclusion that a conventional sting entering the body at its base causes the least, and most easily estimated, interference with

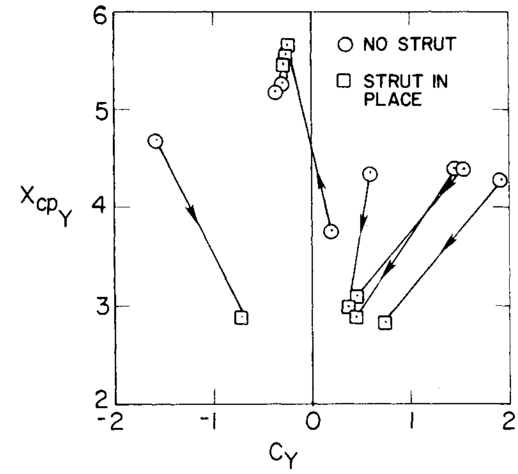

Fig. 11 Effect of leeward midcylinder strut on side force and side-force center of pressure ($M = 0.5$, $\alpha = 40.5$ deg).

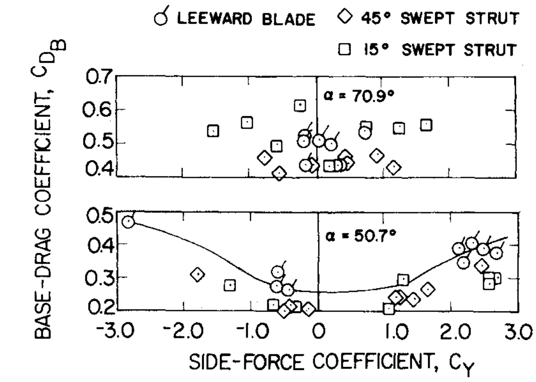

Fig. 12 Effect of leeward midcylinder strut on base pressure ($M = 0.5$).

aerodynamic loads. If a strut support must be used, it should enter the body along the body's windward meridian. Use of an airfoil or flat-sided strut located in the frequently unsymmetrical and/or unsteady wake of the model results in major and unpredictable changes in the loads and base pressure acting on the model; the farther forward this leeward strut is placed, the greater its potential for altering the asymmetric flow.

Two results of this study may be of assistance in understanding the complexities of the asymmetric flow. The first is that all of the aerodynamic properties which appeared to vary widely in a random manner as the model roll position was changed actually correlate remarkably well when plotted as functions of observed side force. The character of the flow asymmetry is felt to be well represented by the side force so that recognizable trends in normal-force amplitude and center of pressure, side-force center of pressure, and base drag emerge.

The second is that it may be possible to control the direction of the flow asymmetry by means of a small trigger. The cases analyzed suggest that a small bump near the nose is very effective if placed near the leeward meridian and very ineffective when near the windward meridian.

Finally, it is concluded that until the occurrence and degree of asymmetry can be controlled in test and flight, it will be necessary to utilize an assortment of triggers in all relevant tests to avoid missing the natural extremes of asymmetry and to obtain deterministic data.

Acknowledgments

The work was performed under Contract F08635-79-C-0119 from Eglin Air Force Base, jointly funded by Eglin AFB and MICOM. Dr. Don Daniel was technical monitor. Dr. Gary Chapman and Gerald Malcolm of NASA Ames provided valuable advice, and Brian Wettlaufer of ARO, Inc. aided in conduct of the test program.

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