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Reduction of the Side Force on Pointed Forebodies Through Add-On Tip Devices

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Subsonic, incompressible aerodynamics of a conical pointed forebody with a cylindrical base is studied at a subcritical Reynolds number of around 10^5. The main objective is to assess effectiveness of delta strakes, porous tips, nose-boom tips, and their combinations in alleviating the undesirable side force. Results suggest that, among the tip devices tested, a delta strake with an aspect ratio of 2 can reduce the side force by around 96% in the angle of attack α range of ± 50 deg and at zero roll ϕ. Even with $\alpha = +50$ deg and ϕ ranging over 0–360 deg, the minimum reduction was observed to be 57%.

Nomenclature

A_b	= base area of cone, $\pi D^2/4$
A_R	= aspect ratio (span)^2/(platform area), $2b/h$
b	= tip-to-tip span of a delta strake
C_N	= coefficient of normal force, normal force/$(q \cdot A_b)$
C_P	= coefficient of pressure, P/q
C_S	= coefficient of side force, side force/$(q \cdot A_b)$
D	= cone base diameter
h	= height of a delta strake
L	= total cone length
L_b	= nose-boom length
L_s	= strake length
P, P_∞	= local and reference freestream static pressures, respectively
q	= freestream dynamic pressure head, $\frac{1}{2}\rho V_\infty^2$
Re	= Reynolds number, $\rho V_\infty D/\mu$
V, V_∞	= local and freestream velocities, respectively
α	= angle of attack
β	= yaw angle
δ	= cone half-angle
μ	= dynamic viscosity
ρ	= density
ϕ	= roll angle (in the circumferential direction), i.e., rotation about the cone axis

I. Introduction

COMBAT agility requirements for present and next generation of fighter airplanes have emphasized the need for controlled flight capability to increasingly high angles of attack. V/STOL type of configurations under study for a variety of military as well as civilian missions, including intercity commuter traffic, also use high-attitude takeoff and descent. Such aircraft commonly employ pointed forebody fuselage. The asymmetric, helical boundary-layer separation has often led to an undesirable side force and the associated yawing moment.

Fluid dynamics of slender bodies at high angles of attack has been a topic of long standing interest to fluid dynamicists. Earlier investigations (1951–1976) were primarily based on the so-called impulse analogy, which describes the development of the wake along the body in terms of the flow behind a two-dimensional cylinder started impulsively from rest. Thomson and Morrison[1] have reviewed this literature quite effectively in their thorough study of spacing, position, and strength of vortices associated with slender cylindrical bodies at large incidence. Most of the earlier efforts were primarily concerned with the in-plane force (force in the plane of the inclination) normal to the axis of the body.

The out-of-plane force, at times referred to as side force, does not exist on bodies of commonly encountered fineness ratio until fairly high angles of inclination and has received attention relatively recently. Most investigations during the period of 1971–1976 focused attention on obtaining experimental data for overall forces associated with bodies of specific geometry. A notable exception is a detailed study by Lamont and Hunt,[2] who, beside reviewing the literature in this period, have reported an experimental investigation of surface pressure on a cylindrical body of circular cross section fitted with various nose shapes for angles of inclination up to 90 deg. The main emphasis is on the side force distribution along the axis of the body and its interpretation in terms of the impulse analogy. Both the time-averaged as well as the time-dependent data were presented and the reason for the unsteadiness examined. In this context, a review of the literature on separation of three-dimensional flows by Wang,[3] which cites 61 references, is also relevant.

The tempo of research activities in the area has shown a marked increase since 1976 with a number of excellent papers touching on different aspects of the problem, including the side force during ablation,[4] pressure and force field distribution,[5] wake structure and the process of vortex breakdown,[6] flow visualization studies,[7,8] and above all, mechanisms for alleviation of the side force.[9,10] Three excellent papers by Ericsson and Reding[11-13] go a long way in briefing an interested researcher about these developments in the field. A paper by Modi et al.[14] and the recent thesis by Stewart[15] also review the literature at some length.

However, the rate at which the new literature continues to appear is truly astonishing. It also suggests importance attached to the subject matter with reference to evolution of the next generation of high-performance airplanes. Current focus appears to be on the understanding of physical parameters contributing to vortex asymmetry and its control as suggested by highly informative investigations of Moskovitz et al.,[16,17] Tavella et al.,[18] Hoang et al.,[19] Blake and Barnhart,[20] and

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Zilliac et al.[21] Furthermore, considerable efforts are directed toward numerical simulation of the complex flow[22-24] and, in some cases, assessment as to the effectiveness of the procedure through comparison with reliable experimental data.[25,26]

With this as background, the paper briefly describes results of an extensive test program aimed at assessing effectiveness of several passive tip devices in reducing the side force at high angles of attack in subsonic incompressible flows.

II. Test Methodology

For the experimental program, a cylindrical base 7 cm in diameter and 10 cm long with a conical forebody formed the basic test model. The hollow aluminum cone with an apex angle of ≈ 28 deg was 15.25 cm (6 in.) long and had a base diameter of 7.82 cm (3 in.). It accommodated up to 40 pressure taps. The static pressure at a tap, typically 0.64 mm in diameter, is conveyed by a polyethylene tube, 1.7-mm i.d., to an externally located pressure transducer. The apex of the cone can be separated at two locations to replace it with desired tip geometries. The cylindrical aft body was connected to a yoke-type vertical support, which was in turn mounted on the wind-tunnel balance platform, such that the angle of attack and yaw inclinations can be adjusted as required. A desired roll orientation can be acquired either by rotating the entire model or the tip about the cone axis.

Thus, even for a given angle of attack, the spatial orientation of the cone with respect to an inertial reference can be different and, hence, the surface roughness profile exposed to the incoming wind. Furthermore, the shaft with a tip is supported in position by a set of bearings, thus permitting roll of the tip independent of the cone. Therefore, depending on the initial orientation of the cone and the tip, the character of the surface roughness even for a given α and ϕ is not unique. It is important to keep this aspect in mind while interpreting the results presented. The side force data were obtained using two independent procedures: strain-gauge balance and integration of the pressure data. The results correlated rather well with an error margin of less than 3%.

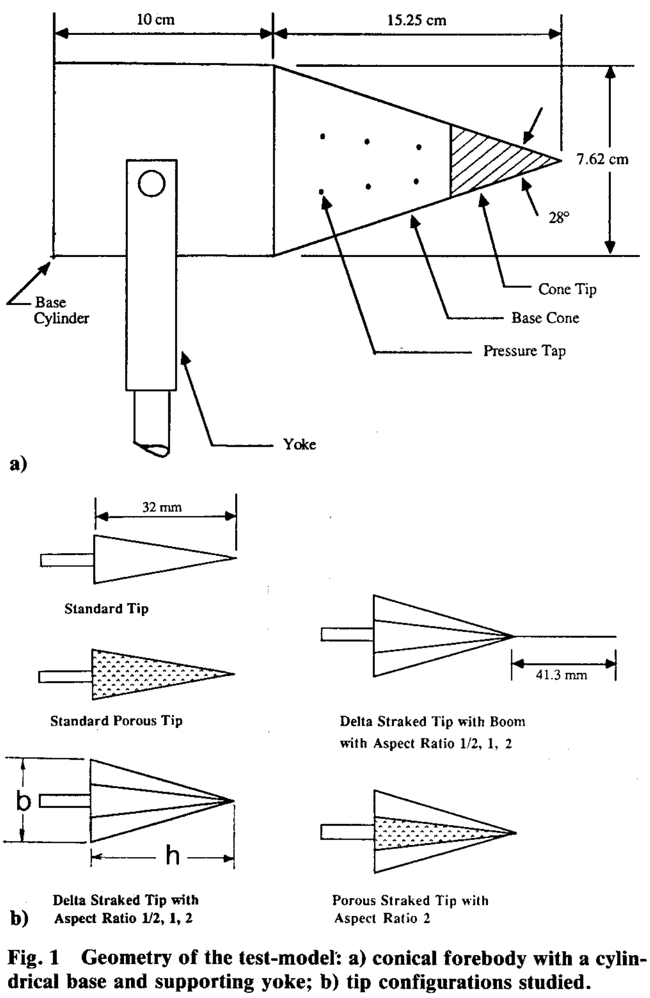


Fig. 1 Geometry of the test-model: a) conical forebody with a cylindrical base and supporting yoke; b) tip configurations studied.

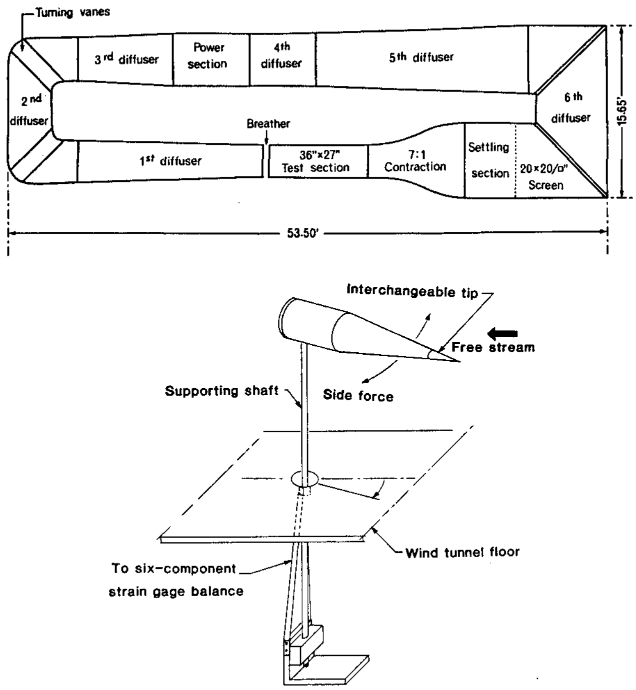


Fig. 2 Schematic diagram of the wind tunnel used in the test program and the model support system.

To minimize the effect of surface roughness on the boundary-layer instability, and hence, to better identify the influence of tip geometry on the side force, the cone model was provided with a smooth mirror finish. With the exception of the nose tips, the entire model was polished to within 5–7 μ surface roughness. The tests focused primarily on a family of delta strakes, a nose boom, a porous tip, and their combinations. Of course, the standard conical tip was also tested extensively to provide base information for comparison. A schematic diagram of the cone model and tip geometries tested is shown in Fig. 1.

The models were tested in a closed-circuit laminar flow tunnel with a test section of 0.69 × 0.91 × 2.44 m. The tunnel is able to produce a stable flow with the speed ranging from 0.3 to 30 m/s at a turbulence level of less than 0.1%. The rectangular cross section, 0.69 × 0.91 m, is provided with 45-deg corner fillets that vary from 15.25 × 15.25 cm to 12.1 × 12.1 cm to partially compensate for the boundary-layer growth. The air speed is measured by a Betz manometer with an accuracy of 0.02 mm of water. The spatial variation of mean velocity in the test section was observed to be less than 0.24%. Figure 2 shows the outline of the wind tunnel and the model support system.

III. Results and Discussion

The amount of information obtained through a systematic test program involving the basic model, add-on tip devices, and their combinations is rather extensive.[27] For conciseness, only a few of the typical results useful in establishing trends are presented here. The standard cone-tip data are presented first, which serve as a reference to assess the effectiveness of the other tip geometries. Typical results for the porous tip, delta strakes with three different aspect ratios (A_R = ½, 1, 2), nose boom, and their combinations follow. In each case, the results were obtained in the angle-of-attack range $\alpha = \pm 50$

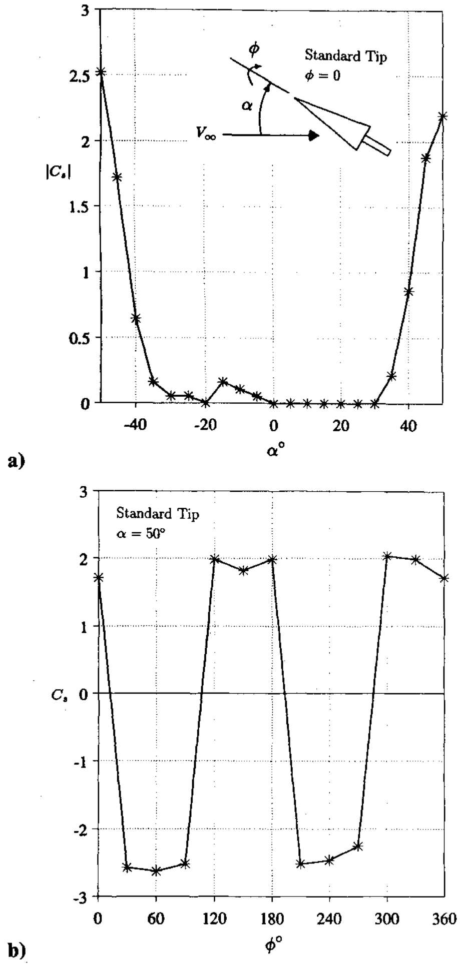


Fig. 3 Variation of the side force coefficient as affected by the angle of attack (pitch, α) and roll ϕ: a) pitch angle varying over the range ± 50 deg for a constant roll of $\phi = 0$; b) effect of roll through 0–360 deg for a constant pitch of $\alpha = 50$ deg.

deg and the roll angle variation through 360 deg at $\alpha = +50$ deg. At higher values of α, the model was susceptible to vibrations due to the turbulent wake. Hence, the results are time-averaged values. The paper records only a small sample of data, however, it is sufficient to assess the potential of the tip devices in reducing the side force.

Standard Cone Tip

Variation in the absolute side force coefficient with the angle of attack at a fixed roll orientation ($\phi = 0$) is shown in Fig. 3. The effect of variation in ϕ at a constant angle of attack of 50 deg is also presented. A steep increase in C_s for $\alpha > \pm 30$ deg and its cyclic change as the cone tip is rotated through 360 deg are as expected. Note, in the present case of the cone model with a tip angle of 28 deg, that the maximum side force coefficient can be as large as 2.5, which is of the same order of magnitude as the lift and drag coefficients.[14]

A comment concerning asymmetry of the side force variation about $\alpha = 0$ would be appropriate. As is well known, the side force is quite susceptible to the tip surface roughness profile exposed to the incoming wind. Obviously, during positive and negative angles of attack, the lower and upper side of the tip (and the cone) are exposed to the freestream, presenting different surface roughness character. This affects the unstable character of the vortex sheets, which is reflected in the difference in the side force. For example, in Fig. 3a, $|C_S| = 2.5$ at $\alpha = +50$ deg but 2.24 at $\alpha = -50$ deg. Depending on the tip geometry and surface condition, the disparity could be substantial. Interference due to the presence of the yoke would also add to the asymmetry. A large number of parameters affect the side force value and most likely all of them are still not accounted for to fully understand this complex phenomenon. On the other hand, effectiveness of the various tip geometries in reducing the side force is unmistakable, however, it should be considered as suggesting trend rather than precise numerical values.

Standard Porous Tip

The earlier study by Stewart[15] showed a porous tip to reduce the side force. The mechanism of the side force reduction was explained through pressure equalization at the tip, which, in turn, promoted the helical vortex symmetry. Unfortunately, as pointed out by Stewart himself, the results may be considered inconclusive as the tip cavity was left unsealed, thus affecting the internal pressure by that at the base of the cone. Obviously, a more systematic test was desirable to assess the effect of the cone-tip porosity. To this end, the cone model was fitted with a new porous tip.

Essentially, the tip was a hollow cone, with 56 pores, each 0.65 mm in diameter. The tip cavity was sealed at its base and mounted at the end of a shaft, which, in turn, was supported by a pair of bearings in the main body of the cone. This permitted the tip to have any desired roll orientation quite readily.

At $\phi = 0$, and over the range of angle of attack of -50 to $+50$ deg, the porous tip showed a significant reduction in the side force (Fig. 4) with the maximum C_S decreasing from 2.5 to 0.35, an 86% reduction! However, as the tip was rolled through 360 deg with the angle of attack held fixed at $\alpha = 50$ deg, the cyclic variation of C_S showed a peak value of around -2.5, i.e., absolutely no change in the magnitude of the side force. This may be attributed to the roughness caused by the relatively large size holes that promote the vortex asym-

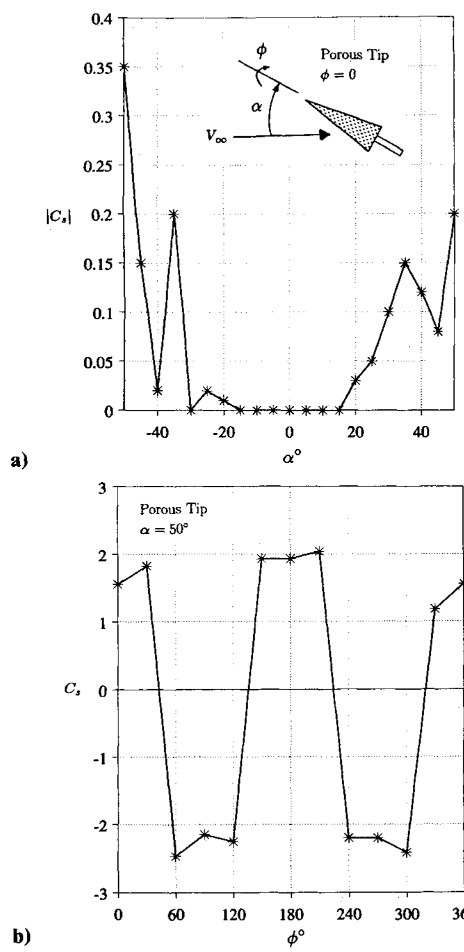


Fig. 4 Effect of porosity on the side force: a) -50 deg $\le \alpha \le 50$ deg, $\phi = 0$; b) $0 \le \phi \le 360$ deg, $\alpha = 50$ deg.

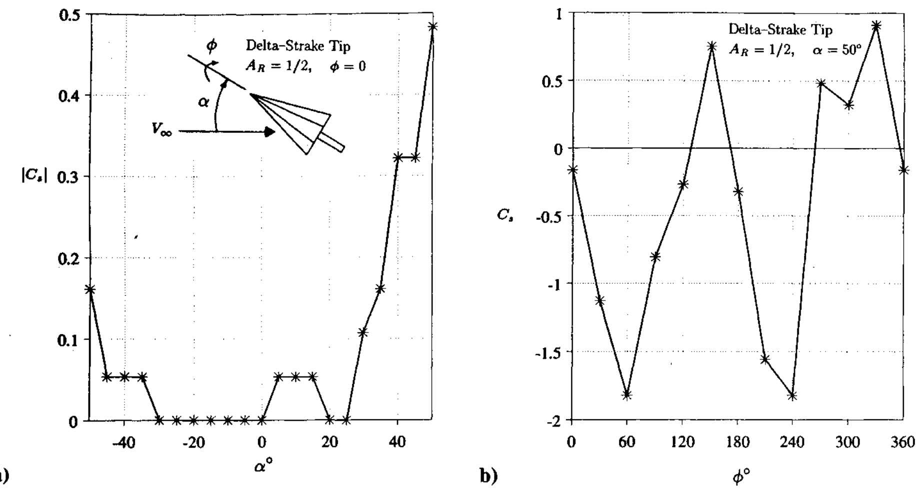


Fig. 5 Plots showing influence of a delta strake with an aspect ratio of ½ on variation of the side force coefficient: a) effect of pitch angle at a constant $\phi = 0$; b) influence of tip roll through 360 deg at a constant pitch of $\alpha = 50$ deg.

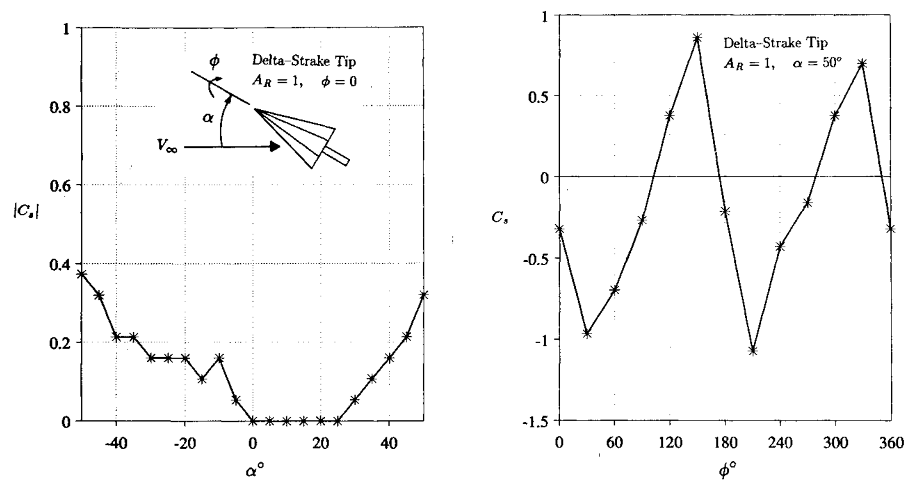


Fig. 6 Plots showing influence of a delta strake of an aspect ratio of 1 in reducing the side force coefficient during both pitch and roll maneuvers.

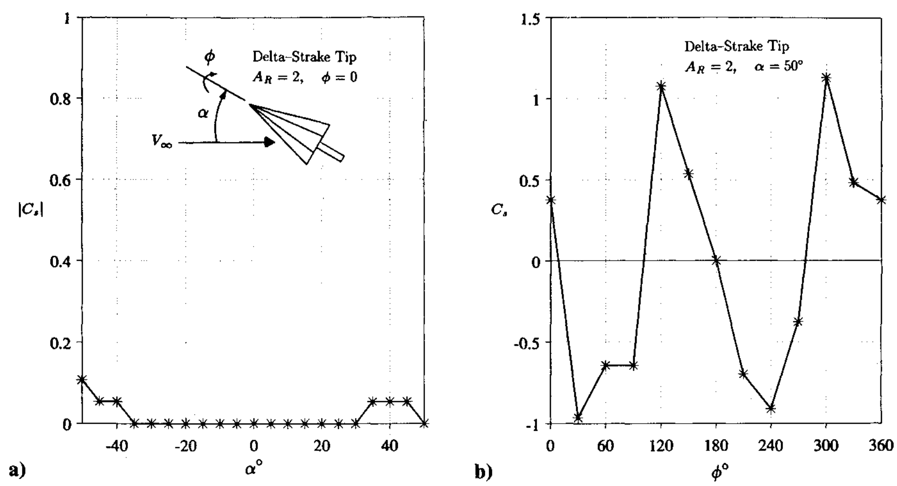


Fig. 7 Among the three delta strakes tested, the one with an aspect ratio of 2 proved to be the most efficient in reducing the side force coefficient: a) pitch angle changing over a range of ± 50 deg with the roll held fixed at $\phi = 0$; b) roll angle varying over the range 0–360 deg at $\alpha = 50$ deg.

metry, thus canceling positive influence of the pressure equalization. A similar test with a second smaller porous tip using fewer pores located close to the tip gave virtually the same results (not shown).

Apparently, to avoid the influence of pore induced surface roughness, it is necessary to use the tip constructed from microscopically porous material. Such tests are in the planning stage. However, the results seem to suggest that the pressure equalization induced by the porous tip does promote the helical vortex symmetry.

Delta-Strake Tips

Three delta strakes with the chordwise length of 32 mm and aspect ratios of ½, 1, and 2 were tested to assess their effectiveness in reducing the side force over a wide range of pitch and roll attitudes. Only a typical set of results are presented in

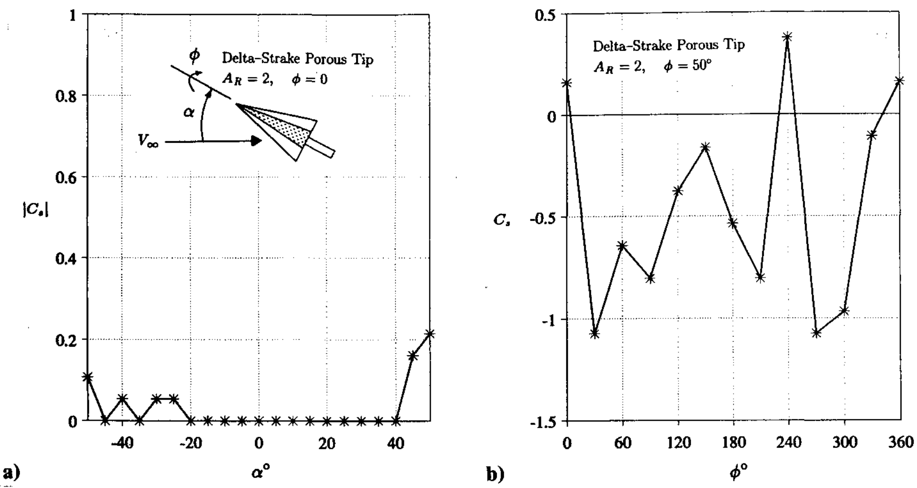


Fig. 8 Effect of the porous tip with a delta strake of $A_R = 2$ on the side force coefficient: a) variation of the pitch angle; b) variation of the roll.

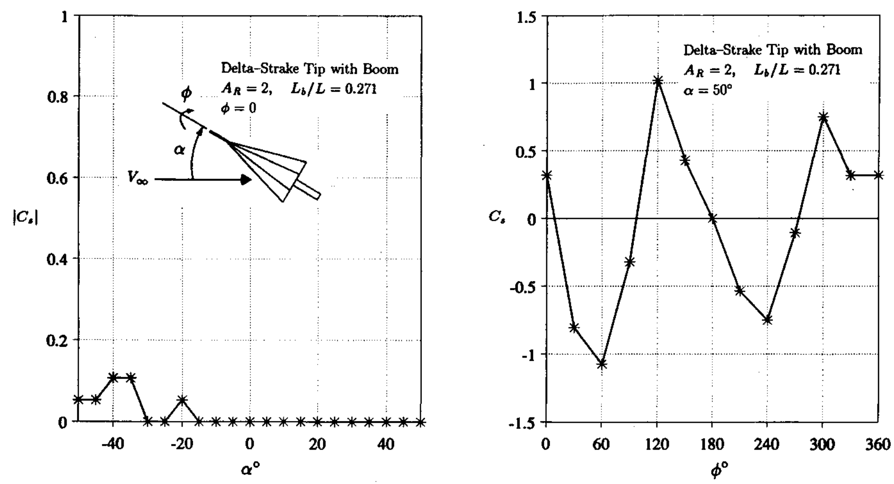
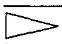
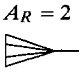
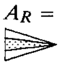


Fig. 9 Plots showing performance of a delta strake ($A_R = 2$) in the presence of a nose boom. Note, there is virtually no change in performance compared to the delta strake by itself, Fig. 7.

Table 1 Comparative merit of the various tip geometries used in the test program[a]

		Percent reduction	
Tip geometry	C_S(max) $\phi = 0$	Zero roll	With roll maneuver at $\alpha = 50$ deg
	2.55		
	0.35	86	3
			
$A_R = ½$	0.48	81	29
$A_R = 1$	0.37	85	58
$A_R = 2$	0.11	96	57
			
$A_R = ½$	0.38	85	12
$A_R = 1$	0.21	92	58
$A_R = 2$	0.11	96	58
			
$A_R = 2$	0.21	92	58

[a]The minimum attainable reduction in the side force coefficient is presented as percentage of the standard tip data for both pitch and role maneuvers.

Fig. 5. For an aspect ratio of ½ and the roll attitude fixed at $\phi = 0$, the maximum side force coefficient observed, over the range of $\alpha = -50$ to $+50$ deg, was 0.48 (Fig. 5a). This represents a reduction of 81%. However, with the model fixed at $\alpha = 50$ deg, and the tip rotated through one revolution in a small increment of 30 deg ($\phi = 0$–360 deg, $\Delta\phi = 30$ deg), the peak absolute side force coefficient ($|C_s|$) rose to 1.82, i.e., a reduction of only 27% (Fig. 5b).

The tests with strakes of aspect ratios 1 and 2 showed essentially the same trend, however, with a progressive improvement in performance as seen in Figs. 6 and 7. The delta strake with an aspect ratio of 1 improved the performance during pitch to 85% ($|C_s|_{max} = 0.37$ at $\phi = 0$). Even during the 360-deg roll, the minimum reduction was found to be at least 57% ($|C_s|_{max} = 1.07$). The delta strake with an aspect ratio of 2 (Fig. 7) virtually eliminated the side force over the entire range of pitch used in the experiment ($|C_s|_{max} = 0.107$, at least a reduction by 96%!). Even with the roll maneuver as before, this add-on tip device continued to reduce the maximum value of side force by at least 56% ($|C_s|_{max} = 1.13$). Thus, the delta strake of aspect ratio 2 appears to be quite promising in reducing the side force. It is of interest to point out that X-29 uses nose strakes to minimize asymmetries in the flowfield.

Delta Strake with Porous Tip or Nose Boom

Earlier studies by Modi et al.[14] and Modi and Stewart[28] have shown that both nose-boom as well as porous tips aid in reducing the side force. The present study with porous tips also showed promising results, as discussed earlier. Thus, it seemed appropriate to explore if the performance of delta strakes can be improved further by using them in conjunction with a nose-boom or porous tip. Representative results with the delta strake of $A_R = 2$ are presented in Figs. 8 and 9. For the case of nose boom, its optimum length of 4.13 cm ($L_b/L = 0.271$) as reported by Modi and Stewart[28] was selected. The wake generated by the nose boom being more regular than the freestream turbulence is expected to reduce instability of the vortex flow associated with the cone. Results suggest that the presence of porous character of the tip of the nose boom does not lead to any further significant improvement in the delta-strake performance.

Table 1 summarizes results obtained with the standard tip, delta strakes, nose boom, etc. In the absence of the roll maneuver, the tips studied can reduce the maximum side force coefficient encountered in the pitch range of − 50 to + 50 deg by a significant amount (at least in the range of 81–96% depending on the tip used). The roll maneuver through 360 deg at a high angle of attack of 50 deg reduces the tip performance, suggesting an adverse effect of the surface roughness and its complex interaction with the separating shear layers. However, even in this extreme situation, the delta strake with $A_R = 2$ is able to reduce the side force by at least 57%

IV. Concluding Remarks

1) The subject of vortex dominated flows has proven to be far more complex both in terms of experimental study and numerical approaches than the first impressions would indicate. As often happens in investigations of aerodynamic phenomena, many uncontrollable parameters appear that not only complicate but sometimes invalidate the test results. In the present case, it was gratifying to note that the carefully planned experiments, with repeatable results, provided reliable information concerning the effectiveness of several tip geometries on the side force reduction.

2) The tests with a 28-deg cone-cylinder model, in the absence of any add-on tip device, gave a large side force coefficient in the range of 2.2–2.55 at an angle of attack of ± 50 deg. Even microscopic variations in the surface roughness near the tip appear to have a significant effect on the side force.

3) A delta strake with an aspect ratio of 2 can virtually eliminate the side force (reduction by 96%) in the angle-of-attack range of ± 50 deg. Even at an α as high as 50 deg and the roll maneuver through 360 deg, the minimum reduction in the side force coefficient was around 50%.

4) The porous tip appears to promote vortex symmetry through pressure communication. This resulted in a drop in the side force coefficient by at least 86%. However, in the present study, the size of the holes being 0.64 mm may, in turn, introduce surface roughness and, hence, lead to additional side force. To better appreciate the effect of pressure communication, the cone tip should be constructed using a microscopically porous material. Such tests are in the planning stage.

5) By incorporating an appropriately chosen size of the nose boom ($L_b/L = 0.27$) with the standard cone tip, the side force coefficient can be reduced by at least 50%. However, precise alignment of the boom with the cone axis is essential during the roll maneuver.

6) The porous character of the cone tip or the presence of the optimum size boom in conjunction with the delta strake does not seem to improve the performance further. Thus, the delta strake appears to be dominant in promoting the vortex symmetry.

7) Such passive procedures for the side force control are indeed quite attractive; however, considerable scope for further study exists to arrive at an optimum configuration. Numerical prediction of the side force for a pointed forebody at high angles of attack is a formidable problem in itself. The presence of tip devices would add to the challenge. There is considerable room for innovation in this general area pertaining to separated flows at high angles of attack.

Acknowledgments

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