control inputs has been confirmed to be satisfactory by numerical simulations.[5,7]

Coordinated Rolls

In a coordinated roll, sideslip is maintained equal to zero, the rudder being appropriately deflected for this purpose. PSS solutions for the previously mentioned model with an extra condition, $\beta = 0$, are solved and the required rudder deflection simultaneously determined. These are plotted in Figs. 1 and 3 by full lines marked with filled circles. In the absence of any sideslip, the roll rate shows, as expected, an ideal linear relation with aileron deflection. However, the PSS roll rate for this case in Fig. 1 is unstable for δa beyond -8 deg. This has been verified by numerical simulation for a solution point (filled circle of Figs. 1 and 3) of $\delta a = -8.6$ deg. The divergence in α and β has been recorded in Fig. 4. In any case, the maximum achievable stable roll rate is about the same for either of the curves in Fig. 1.

The $\delta r - \delta a$ curve in Fig. 3 for a coordinated roll is nonlinear with more rudder deflection being needed to maintain zero sideslip for large aileron deflections. If a linear interconnect were derived from this curve by taking the interconnect constant k to be the slope at the origin, the value of k would turn out to be much less than the critical value of -2.05 required to avoid jump.

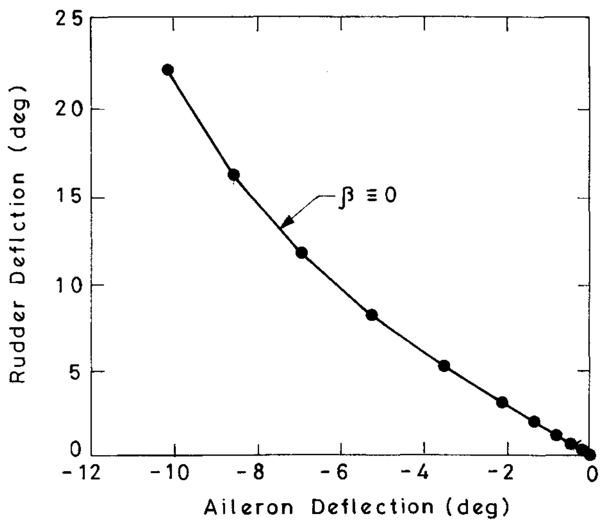

Fig. 3 Rudder deflection solution with varying aileron deflection for zero sideslip case.

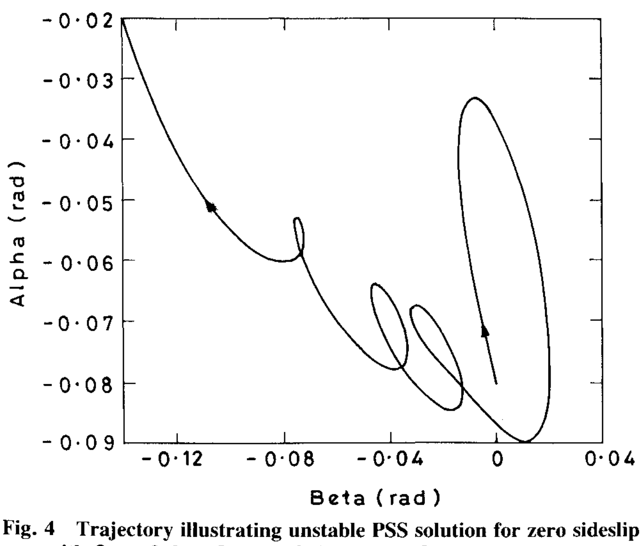

Fig. 4 Trajectory illustrating unstable PSS solution for zero sideslip case with $\delta e = 2$ deg, $\delta a = -8.6$ deg, and $\delta r = 16.3$ deg.

Discussion

Coordinated rolling gives an ideal linear $p - \delta a$ curve, and ensures zero β for all conditions; however, this requires a nonlinear ARI relationship. The PSS solutions for a coordinated roll are unstable beyond $\delta a = -8$ deg. Although, the maximum achievable stable roll rate is comparable to that obtained in the previous study,[5] the onset of instability is sudden.

On the other hand, the PSS solutions obtained from a linear ARI using $k = -2.35$ reported in Ref. 5 show a gradual saturation of the roll rate. The eventual instability around $\delta a = -18$ deg is oscillatory. This solution also gives a larger range of usable δa values, though there is no significant advantage in terms of roll rate. Also, the sideslip in this case (Fig. 2) is not exactly zero, but well-restricted over the required range of aileron deflections.

Conclusions

The present study has shown that the condition for nonexistence of jump based on bifurcation theory cannot be routinely replaced by one derived from the requirement of a coordinated roll, even when the formulation contains inertial coupling terms.

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Effects of Spanwise Blowing on a Delta Wing with Vortex Flaps

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Introduction

SEVERAL concepts to enhance and control the formation of leading-edge vortices on slender swept wings have been studied. Typically, concepts that significantly increase per-

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formance as well as the flight envelope, augment and control vortex formation and delay vortex breakdown (i.e., an axial deceleration of the vortex core, with a concomitant increase in vortical diameter[1]), and are essentially active (or powered) in nature. They include both spanwise[2–4] and tangential blowing.[5] Spanwise blowing is accomplished by ejecting a jet of air, usually parallel to the wing leading edge, from a chordwise station close to the wing apex (10% of the wing root chord has been found to be most effective for a planar 60-deg delta[2,3]). Tangential blowing entails discharging a jet of air along the wing's leading edge tangentially to the local surface.

Of these, tangential blowing appears to be most effective in extending the flight envelope. Flow separation from the wing's leading edges is controlled through regulating the position of the crossflow separation points, and thus, the vortex trajectories.[5] Flow control up to 60-deg angle of attack[5] may be realized. Although this method of active flow control is effective, it perpetuates one of the primary drawbacks of slender wings, i.e., poor lift generation at low incidence. This is a result of tangential blowing delaying separation, and thus, lift enhancement due to vortex action, to higher angles of attack.

Depending on the planform, spanwise blowing can provide additional lift from moderate to high angles of attack.[2] This is attributed to blowing enhancing and controlling the leading-edge vortex system[3] through the process of flow entrainment. Vortex breakdown may also be delayed to a moderately higher α. Generally, for highly swept wings with naturally occurring vortex flow, effects due to blowing are mostly seen at high angle of attack. For less swept wings, blowing may cause vortex formation at lower α than would normally occur, such that an increase in lift due to vortex action at moderate α (as well as at high angles of attack) may also be present.

Leading-edge vortex flaps (LEVFs) have been shown to be successful devices to improve the efficiency of slender swept wings[6–8] and strake-wing configurations.[9] An effective vortex flap works by concentrating the suction of the leading-edge vortex on the flap, so that a thrust force may result. Although flap deflection results in a decrease in lift (due to a partial suppression of vortex formation, as well as a moderate reduction in the attached flow lift component[8]), the accompanying decrease in drag results in a superior lift-to-drag ratio. Vortex spillage, i.e., the leading-edge vortex expanding and moving progressively inboard off the vortex flap with increasing α, thus resulting in a decrease in recovered thrust, provides a limitation to LEVF efficiency.

In this Note, a wind-tunnel investigation into the effects of spanwise blowing on a 60-deg delta wing with a vortex flap is detailed. Blowing may provide both an increase in lift, as well as a reduction in drag, by augmenting the leading-edge vortex system and thus increasing suction on the flap, as well as by delaying vortex breakdown. An appropriately placed nozzle may additionally increase the effectiveness of the vortex flaps, essentially by trapping the vortex on the flap, and so reducing spillage.

Equipment and Procedure

Details of the wind-tunnel model are given in Fig. 1. To simplify the implementation of the blowing system, a reflection plane model was used. The wing planform was that of a cropped 60-deg delta, with a taper ratio of 0.125 for the planar wing, and was manufactured from 4.5-mm-thick aluminum plate. The trailing edge of the wing was beveled. A constant chord vortex flap, with a deflection angle of 30 deg was used in the tests, as this angle has been shown to be effective for this wing configuration.[7] To make the results more representative of what may be implemented in practice, the size of the vortex flap is somewhat smaller than that considered as optimal in Ref. 7 (and corresponds to the next smallest flap tested in that investigation). The nozzle's internal diameter was 3 mm. It was positioned parallel to the wing

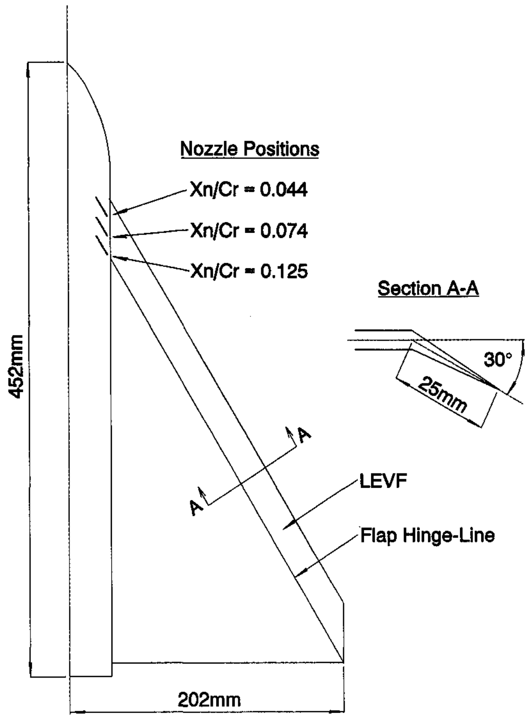

Fig. 1 Model geometry.

leading edge, and at three chordwise stations on the LEVF, these being $x_n/c_r = 0.125$ (i.e., above the flap hinge line), $x_n/c_r = 0.074$, and $x_n/c_r = 0.044$, where x_n/c_r represents the nondimensional chordwise nozzle position, measured from the wing apex. The vertical placement of the nozzle above the flap surface was not varied, as this parameter has been shown to have a marginal effect on spanwise blowing performance.[3] As in Ref. 3, a vertical displacement of the nozzle by one nozzle diameter above the upper surface of the flap was used. A compressed air supply with a maximum reservoir pressure of 620 kPa (90 psi) was available to supply air to the system. The jet-momentum coefficient C_μ was determined using a British Standard orifice plate, and a static pressure and a temperature tapping at the nozzle. Care was taken to ensure that no spurious loads due to the piping were transferred to the wind-tunnel balance. The investigation was undertaken in a low-speed continuous wind tunnel. The tests were undertaken at 30 m/s, corresponding to a wing root chord Reynolds number of 0.65×10^6. The model angle of attack was varied from 0 to 34 deg. All coefficients were nondimensionalized by the wing area plus the projected vortex flap area. To establish the true aerodynamic loads resulting from spanwise blowing, tare values were determined for each test. For each specific C_μ, the model was pitched through the angle-of-attack test range, with the wind tunnel off. These values were then subtracted from the corresponding test results with the tunnel on.

Discussion

Space limitations do not allow the inclusion of data showing the effect of nozzle chordwise position on lift C_L and drag $C_D - C_{D\min}$. However, the results showed that for the present vortex flap configuration, moving the nozzle rearwards reduced lift, as well as increased drag. The foremost nozzle position ($x_n/c_r = 0.044$) was used in the subsequent tests, to investigate possible performance improvements.

Figures 2a and 2b show the effect of C_μ on lift and drag, respectively. To put the data in perspective, graphs representing no leading-edge thrust plus vortex lift (determined using Polhamus' suction analogy[10,11]), as well as 100% leading-edge suction are shown with the blowing results in these

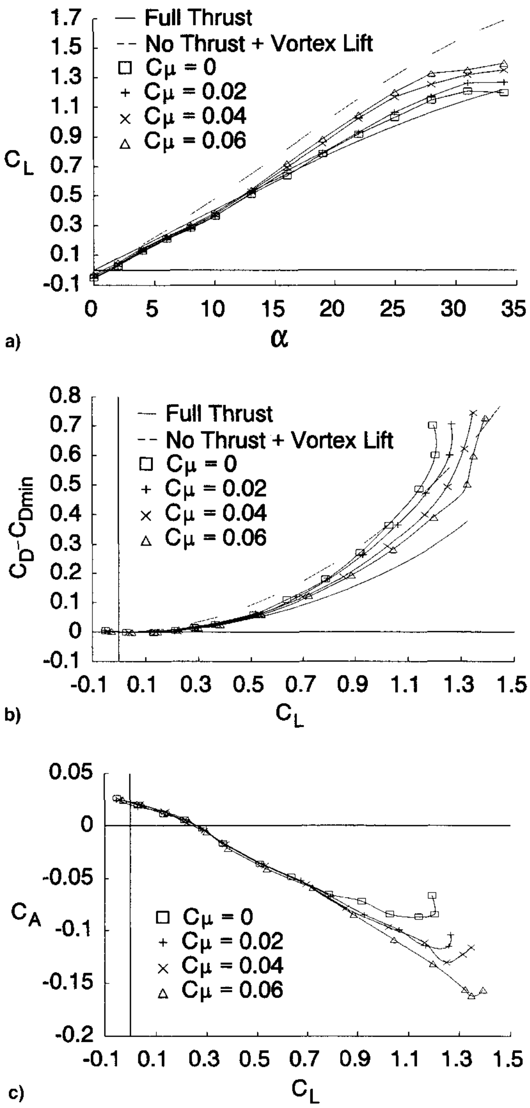

Fig. 2 Effect of C_μ on force coefficient data, x_n/c_r = 0.044: a) lift, b) drag, and c) axial force coefficients.

figures. These two graphs were determined for the equivalent planar wing to that tested, i.e., with the flaps planar. As the wing was cropped, both these graphs additionally incorporate lift and drag due to vortex lift developed along the wing side edge.[10-12] To facilitate comparison between theory and experiment, the drag results are presented in $C_D - C_{D\min}$ form. However, as would be expected due to the removal of tare values, the variation of $C_{D\min}$ with C_μ was marginal. Bradley and Wray[2] have suggested that the effect of high blowing rates on a planar planform is essentially to "increase the lift to the full vortex lift level predicted by theory." This is achieved by delaying the progression of vortex breakdown from the trailing edge to the wing apex. Thus, the graph of no leading-edge thrust plus vortex lift may be considered to represent a corresponding planar configuration with a high jet momentum coefficient.

At low to moderate α ($\alpha < 13$ deg), blowing is seen to have minimal effect on C_L (Fig. 2a), a result which, as mentioned previously, has been found in other studies[2,4] for highly swept wings. Beyond approximately 13 deg, lift is seen to increase progressively with C_μ, with marked lift increases being present at high α compared to the case where $C_\mu = 0$. The nonlinearity of the lift graphs is also seen to increase with blowing rate. Figure 2a demonstrates that at high α, $C_\mu = 0.06$ develops lift values approaching the planar configuration with no thrust plus vortex lift. Substantial reductions in drag compared to $C_\mu = 0$ are evident (see Fig. 2b) at lift coefficients >0.5, and these drag reductions increase with blowing rate. It may also be seen that all the LEVF blowing variations develop almost full thrust for $C_L < 0.5$.

To investigate the effect of blowing on the thrust generated by the LEVFs, the axial force coefficient C_A is presented as a function of lift coefficient in Fig. 2c. It is noteworthy that only beyond a lift coefficient of approximately 0.7 does C_A increase over that for the case where $C_\mu = 0$. However, as shown in Figs. 2a and 2b, increases in lift and reductions in drag are present from a C_L of approximately 0.5. This suggests that for $C_L < 0.7$, lower C_D values are essentially due to the reduction in required α for a given C_L. At lift coefficients greater than 0.7, drag reduction is due both to greater thrust from the flap, as well as the increase in lift. The observed increase in the axial force coefficient compared to $C_\mu = 0$ beyond a lift coefficient of 0.7, does suggest that the leading-edge vortex may be trapped on the flap to greater angles of attack than with no blowing.

Summary and Conclusions

A wind-tunnel investigation was conducted to ascertain the effects of spanwise blowing on a delta wing with a leading-edge vortex flap. In addition to the usual lift-enhancing effects of blowing, increases in thrust from the flap may also be present.

The study suggests that spanwise blowing can offer a relatively simple mechanism by which the performance of leading-edge vortex flaps can be improved. The experimental results showed that blowing generates substantial increases in lift beyond $\alpha = 13$ deg. These lift increases, in addition to increased thrust from the vortex flap, resulted in marked reductions in drag. Blowing was seen to augment the axial force coefficient for $C_L > 0.7$.

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Probe Interference on Flow Measurements in Propeller near Slipstream

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Introduction

THE use of pressure probes for flow surveys has long been an accepted practice and has been applied to propeller flowfield measurements.[1–5] The question of probe or probe support interference on the flow measurements appears not to have been addressed in published literature, apart from a limited discussion in Ref. 5.

In connection with a flow survey in the near slipstream of a propeller, nacelle mounted on a semispan model,[5] using the five-hole probe assembly shown in Fig. 1, it was discovered that the power requirement for a given propeller rpm was sensitive to the angular orientation of the rakes. Furthermore, it was found that with the assembly removed, the power requirement was substantially reduced from that required with the rakes present.

These findings suggested that the five-hole probe assembly interfered with the flow it was designed to measure. For instance, the swirl angle, that is directly related to the torque/power, should consequently be higher with the rakes present than without the rakes for a given rpm. Intuitively, one would think that the presence of the rakes would reduce the swirl angle.

Experimental Technique

An investigation was thus launched to obtain a measure of the possible interference the rake assembly could have on the swirl angle. The tests were performed on an "isolated" nacelle, that was strut-mounted on the wind-tunnel sidewall balance (Fig. 2). Two similar 15-in.-diam propellers were used, one with the blade angle set at 52 deg (at 75% radius), and the other at 58 deg.

Flow measurements were performed using the rake assembly shown in Fig. 1. In addition, a single nonintrusive five-hole probe was used, matching the most inner probe of one of the rakes at 45% radius ($r/R = 0.45$) (Fig. 2). In both cases the probe heads were positioned 1 in. behind the propeller plane. Propeller torque was measured by a torque meter, integral with the propeller drive shafting.

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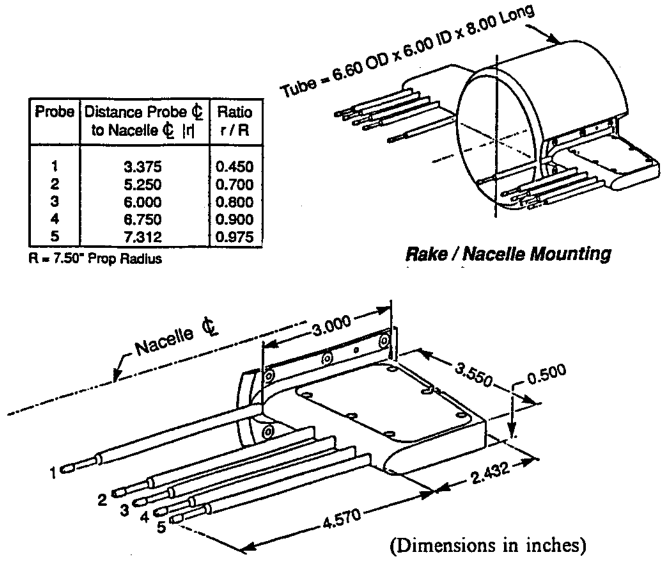

Probe	Distance Probe ℄ to Nacelle ℄ |r|	Ratio r/R
1	3.375	0.450
2	5.250	0.700
3	6.000	0.800
4	6.750	0.900
5	7.312	0.975

Fig. 1 Five-hole probe rake assembly.

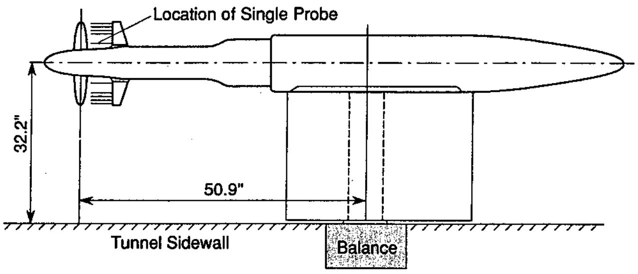

Fig. 2 Propeller test rig with flow survey rakes.

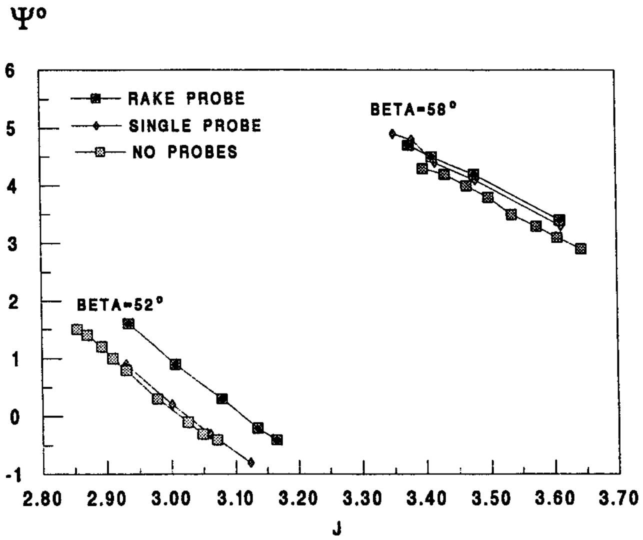

Fig. 3 Comparison of swirl angle data between single probe, rake probe and no probes, $r/R = 0.45$, $M = 0.7$

The investigation was carried out in the IAR 1.5-m × 1.5-m wind tunnel and restricted to Mach number 0.7 and a Reynolds number of 5.6×10^6/ft.

Results and Discussion

A comparison of swirl angle data from the single probe and the corresponding rake probe measurements for the two propellers is shown in Fig. 3 as function of the advance ratio *J*. For a blade angle BETA = 52 deg, the difference between the rake probe and single probe data is very pronounced, with