Jet Spoiler as a Yaw Control Device

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Thin high-velocity jets exiting normal to the wing surface from spanwise slots are investigated experimentally as a means of generating yaw control forces. Jets exiting simultaneously from the upper and lower surfaces as well as a single jet configuration are studied. It is found that this concept can generate significant yawing moment with very modest lift penalty.

Nomenclature

b = span of the semispan model
c = wing chord
c_j = jet slot length
C_ℓ = rolling moment coefficient
C_L = lift coefficient
C_n = yawing moment coefficient
C_p = pressure coefficient
C_μ = jet momentum coefficient
h = vertical projection of equivalent solid spoiler, percent chord
k = proportionality constant
U_∞ = freestream velocity
v_j = jet exit velocity averaged over slot area
V = wind-off jet velocity along slot centerline
x = chordwise coordinate from leading edge
y = spanwise coordinate from wing center
z = coordinate normal to wing upper surface
ΔC_d = change of local drag coefficient
ΔC_L = change of local lift coefficient
α = angle of attack
δ_j = jet slot width
η = nondimensional spanwise coordinate (y/b) from wing root
ξ = nondimensional chordwise coordinate (x/c) from wing leading edge

Introduction

THE need to explore ways of achieving aerodynamic control forces without the intervention of deflecting solid surfaces has arisen in recent years. Among the techniques to produce aerodynamic forces in such ways that no deflecting solid surfaces are involved are a variety of jet and blowing schemes. The better-known ones are circulation control and jet flaps, which modulate lift by introducing supercirculation, and lateral blowing with wingtip ejection, which produces changes in lift by an effective enlargement of the wingspan. A variety of direct thrust jet arrangements have also been considered, where the controlling forces result from direct thrust vectoring. The concept studied here is illustrated in Fig. 1. It consists of thin high-velocity jets that exit normal to the wing surface from spanwise slots. The jets interfere with the stream surrounding the wing, causing localized separation. The modulating aerodynamic forces result from the presence of such separation and from the vortical character of the three-dimensional flowfield. The jet spoiler concept has been explored in the past in the context of missile aerodynamics as a means of generating rolling moments[1–3] in primarily supersonic regimes. In those cases, the yawing moments produced by the jet spoiler were considerably smaller than the rolling moments. The different emphasis of the present investigation, where yawing forces are the primary objective, leads to a different arrangement of the jet spoiler. In the work concerning missiles, the jet was located very near the trailing edge of the rocket fins in order to enhance the forces normal to the fin plane. The source of high-pressure air was to be provided by the ambient flow through ram inlets at the fin tips. In the present case, where the resultant normal forces are to be minimized, the jet slot is located near the maximum thickness station of the airfoil, and an external source of high pressure is anticipated.

A concept of identical nature to the one studied here was conceived by Jack et al.[4] in a patent on a speed control system for windmills. In their scheme, two symmetrically positioned jets at either side of a Darrieus-type wind turbine blade were proposed as a means of stalling the flowfield about the blade. The resulting drag modulation could be used to control the wind turbine setting.

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Experimental Setup

The wind tunnel had a test cross section of 0.457 × 0.457 m, and the tests were run with a wind speed of 36.6 m/s. The half-span wind-tunnel model is shown in Fig. 2. It consisted of a straight wing with an NACA 0018 cross-section profile, a half-span of 0.23 m, and an aspect ratio of 3.14. The model was fitted with 192 pressure taps. The two jet slots, 0.05715 m in length and 0.0015 m in width, were symmetrically located on the upper and lower surfaces. The source of high-pressure air for the jets was a centrifugal blower with a 0–15,000 Pa range. The aerodynamic coefficients were obtained by integration of the pressure on the wing surface. Flow surveys in the wake of the wing were conducted with a five-hole probe, mapping the flowfield through a computer-controlled traverse mechanism.

Results and Discussion

The three-dimensional view shown in Fig. 3 indicates a high-pressure region ahead of the jet and a region of lowered pressure behind it. The high-pressure region is consistent with previous observations in two-dimensional inviscid calculations[5] and in two-dimensional experiments.[6] This increment in pressure is a response to the jet behaving as if it were a solid body, effectively displacing the fluid away from the wing surface. The origin of the reduced pressure region downstream of the jet can be understood by observing the difference between the one- and two-sided blowing cases illustrated in Figs. 4 and 5. The two-sided blowing case produces significantly less suction behind the jet. The jet velocity survey of Fig. 6 indicates considerable skewness of the two-sided blowing case compared to the one-sided case. For each jet, the three-dimensional flowfield should consist of a pair of counterrotating vortices that interact with the single tip vortex. The more even velocity distribution of the one-sided blowing case leads to a better-defined pair of counterrotating vortices, causing more intense suction forces. This fact is clearly shown in the flow mappings of Figs. 7 and 8. The one-sided case shows two vortices. One of them can be identified with that arising from the inboard edge of the jet; the other constitutes the wingtip vortex, which has engulfed the vortex originating from the outboard edge of the jet. In the two-sided case, however, the inboard vortex appears to be absent, the wingtip vortex being the dominant structure. The reason for the skewness of the two-sided blowing case is the absence of stagnant conditions in the plenum. This is due to the requirement that like values of C_μ for the two cases, with the definition

$$C_\mu = 2\frac{\delta_j c_j}{cb}\left[\frac{V_j}{U_\infty}\right]^2 \tag{1}$$

imply twice as much mass flow in the two-sided case.

Experiments on jets issuing from a flat plate with high-subsonic and supersonic freestream speeds[7] have shown the same type of chordwise pressure distribution. The pressure distribution is also qualitatively similar in the case of a solid spoiler.[7]

The effect of the redistribution of the surface pressure when blowing is applied is a change in the local drag coefficient; this change causes the yawing moment. If the jet slot is located near the airfoil maximum thickness station, as is the case here, both the increase in pressure upstream and the suction downstream of the slot contribute to a local drag increase. This location also causes a modest cancellation of the components of force normal to the wing chord, thus having a very small impact on lift, as can be seen in Fig. 9. This counteraction also results in small rolling moment coupling; a feature desirable in this context.

The local drag distributions shown in Figs. 10 and 11 suggest that one-sided blowing is significantly more efficient when the jet exits from the upper surface. This is expected, since decreasing the speed of the high-velocity stream on the upper surface implies a higher induced pressure than a corresponding decrease on the lower surface. The more concentrated drag distribution shown in Fig. 11 indicates that, for negative angle of attack, the wing vortex more effectively distorts the counterrotating vortex pair formed by the jet. The two peaks observed in Fig. 13 for intense blowing are an indication of the distancing of the wingtip vortex from the jet vortices, which are less affected by the former. Comparing Figs. 11 and 12, it can be inferred that superposition of effects does not apply for the present configurations. Figure 14 shows that the yawing moment in the one-sided case is a fairly weak function of angle of attack in the range -2 deg$<\alpha<2$ deg. The yawing moment is defined as follows:

$$C_n = \frac{1}{4}\int_0^1 \eta \Delta C_d \mathrm{d}\eta \tag{2}$$

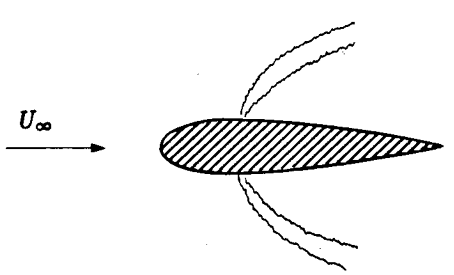

Fig. 1 Jet spoiler concept.

Figure 15 confirms that, in this particular case, this concept is less effective in the two-sided blowing configuration, with the dependence on angle of attack also being stronger. In the two-sided case, the yawing moment is a symmetrical function about $\alpha = 0$ deg.

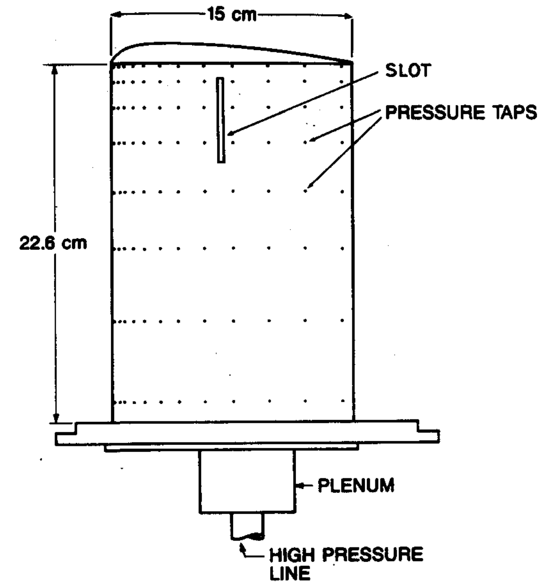

Fig. 2 Wind-tunnel model.

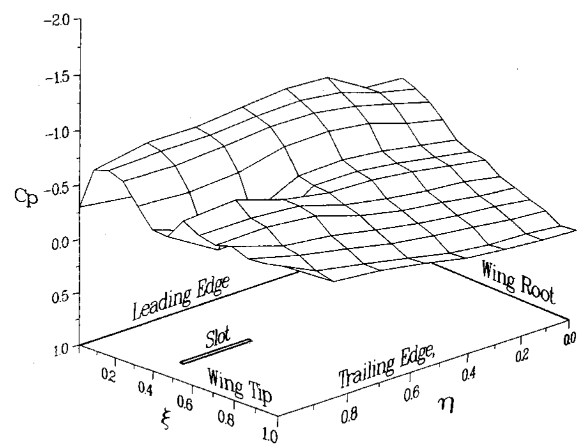

Fig. 3 Pressure distribution on upper surface, one-sided configuration; $\alpha = 8$ deg, $C_\mu = 0.005$.

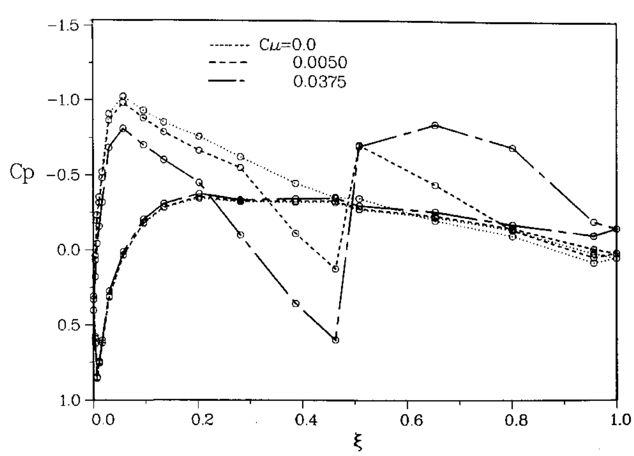

Fig. 4 Chordwise pressure distribution, one-sided configuration; $\alpha = 6$ deg, $\eta = 0.84$.

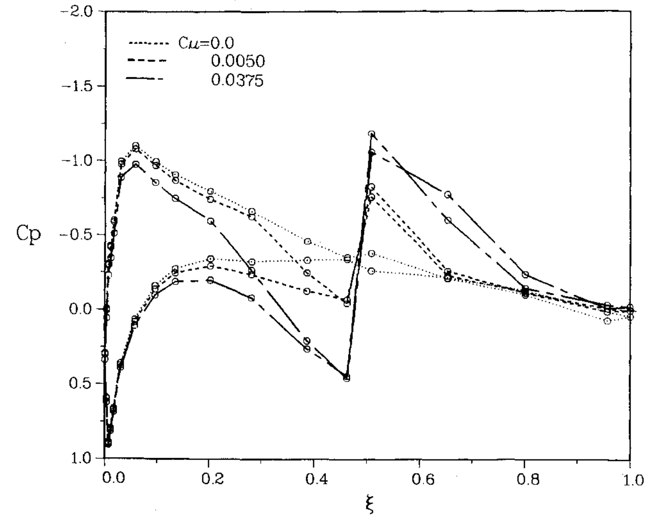

Fig. 5 Chordwise pressure distribution, two-sided configuration; $\alpha = 6$ deg, $\eta = 0.84$.

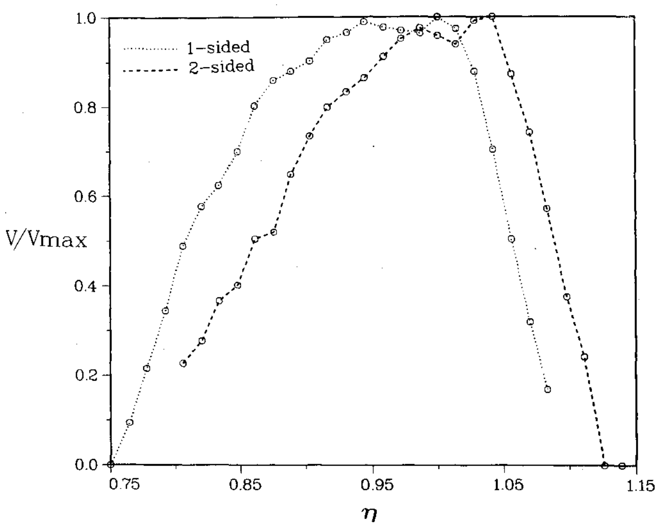

Fig. 6 Jet velocity survey, 0.0824 m from slot.

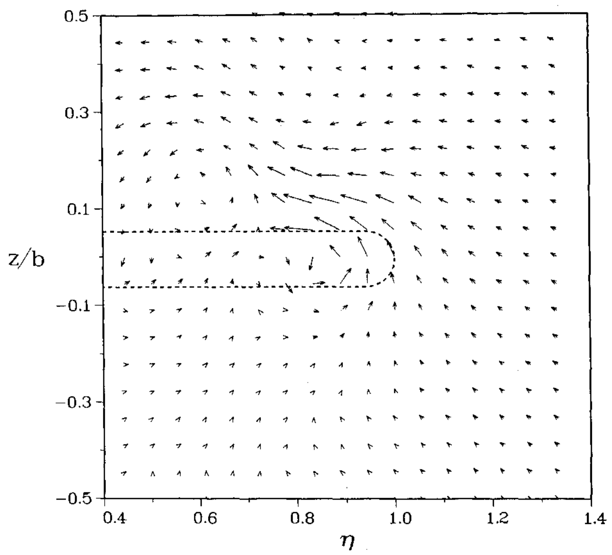

Fig. 7 Flowfield mapping, one-sided configuration; $\alpha = 2$ deg, $C_\mu = 0.0375$, $\xi = 2.4$.

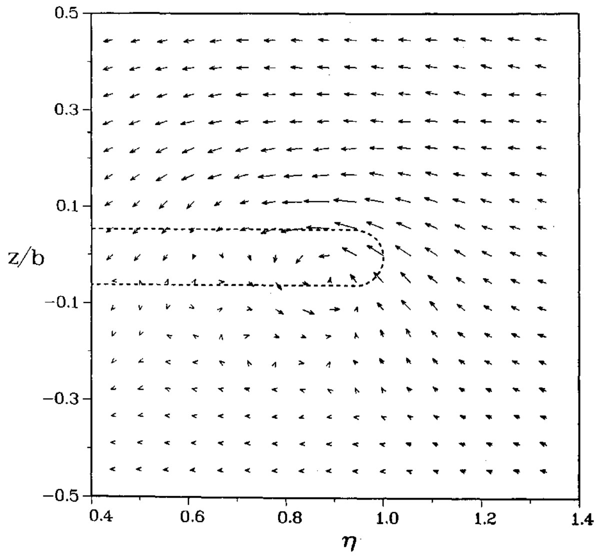

Fig. 8 Flowfield mapping, two-sided configuration; $\alpha = 2$ deg, $C_\mu = 0.0375$, $\xi = 2.4$.

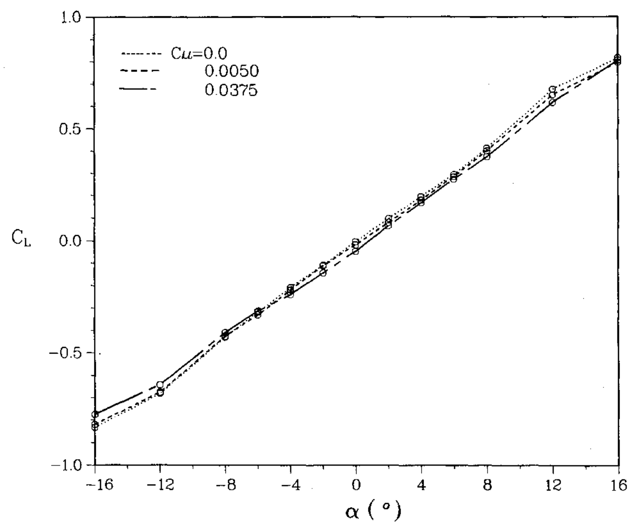

Fig. 9 Effect of blowing on lift, one-sided configuration.

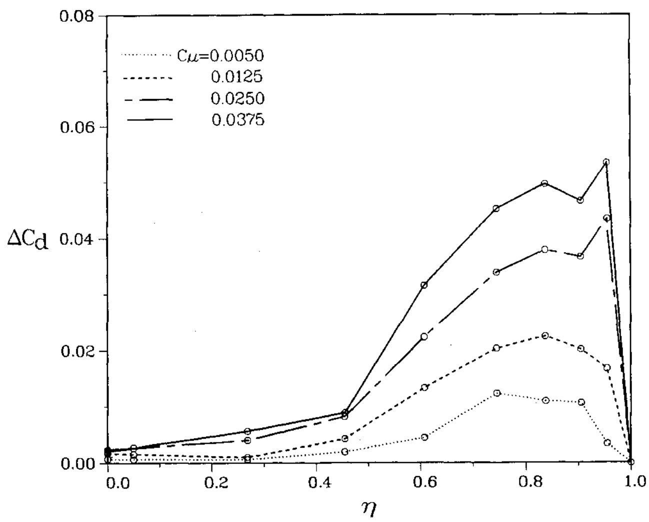

Fig. 10 Local drag increment, one-sided configuration; $\alpha = 6$ deg.

The rolling moment is defined as

$$C_\ell \equiv \frac{1}{4}\int_0^1 \eta \Delta C_L \mathrm{d}\eta \tag{3}$$

Figures 16 and 17 show that rolling and yawing moments are comparable, with the rolling moments exhibiting a rather erratic dependency.

Further insight into the behavior of this concept can be gained by analyzing the relationship between yawing moment and blowing intensity. By averaging the yawing moments produced by the one-sided case in the range 0 deg $< \alpha <$ 12 deg, where the dependence on α is fairly weak, the logarithmic plot in Fig. 18 is generated. Linear regression gives

$$C_n = kC_\mu^{0.85} \tag{4}$$

with k a proportionality constant, presumably dependent on airfoil thickness and jet location. The relevant feature is that this power is less than 1, implying higher sensitivity of yawing moment to blowing at lower blowing intensities. This type of nonlinear dependence on blowing intensity is typical of blowing concepts where a significant component of the phenomenon is of inviscid character, such as jet flaps,[8] lateral wingtip blowing,[9] and delta wing leading-edge blowing schemes.[10]

A practical assessment of the jet spoiler potential to effect yaw control is obtained from comparison with the performance of a typical solid spoiler. For this purpose, the ex-

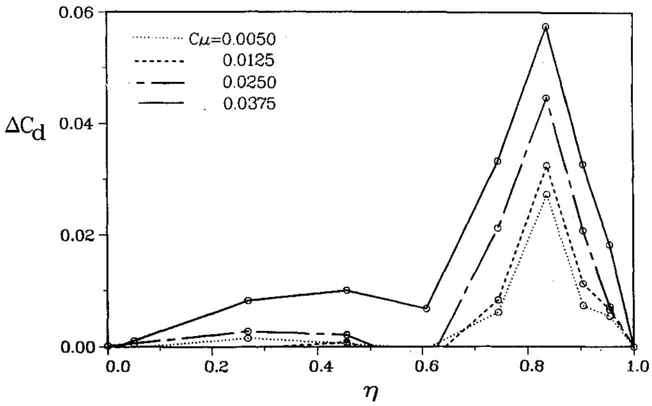

Fig. 11 Local drag increment, one-sided configuration; $\alpha = 6$ deg.

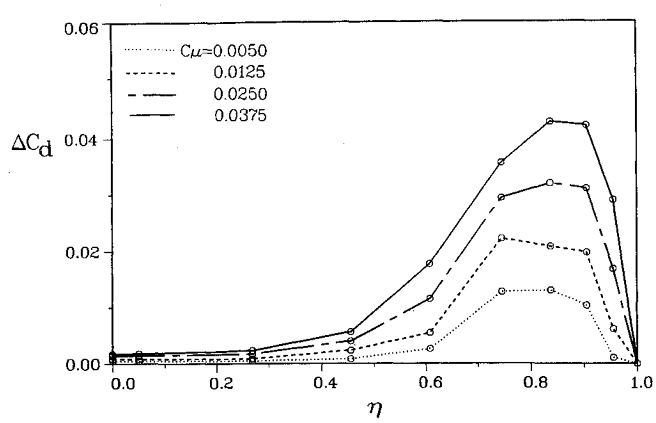

Fig. 12 Local drag increment, two-sided configuration; $\alpha = 6$ deg.

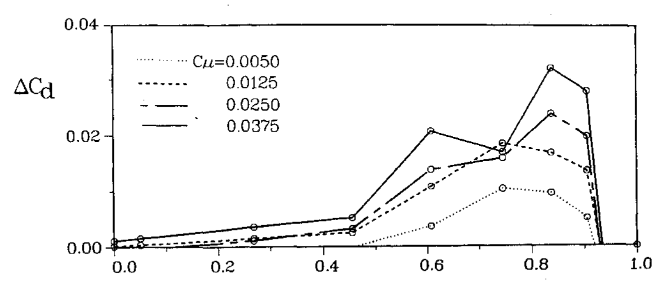

Fig. 13 Local drag increment, two-sided configuration; $\alpha = 12$ deg.

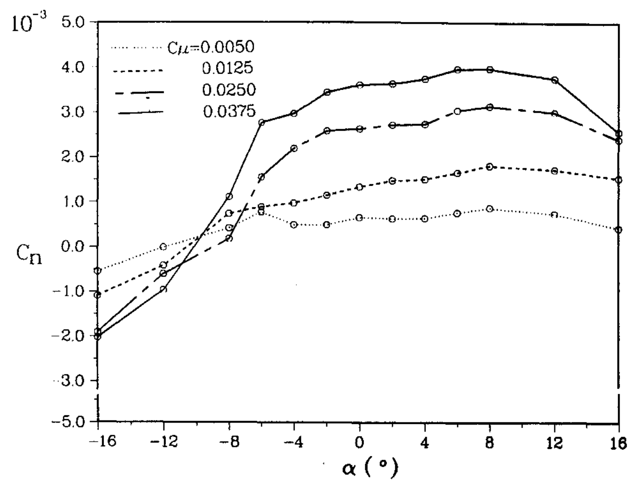

Fig. 14 Yawing moment coefficient, one-sided configuration.

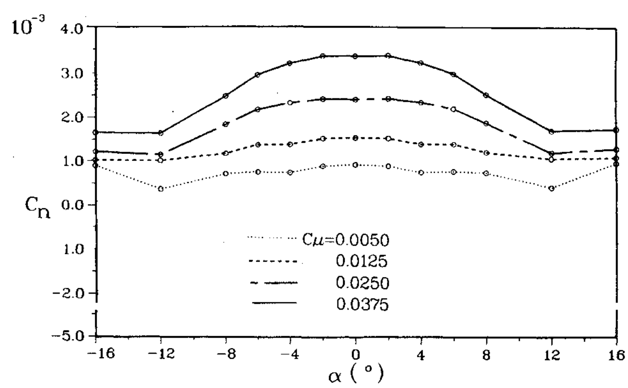

Fig. 15 Yawing moment coefficient, two-sided configuration.

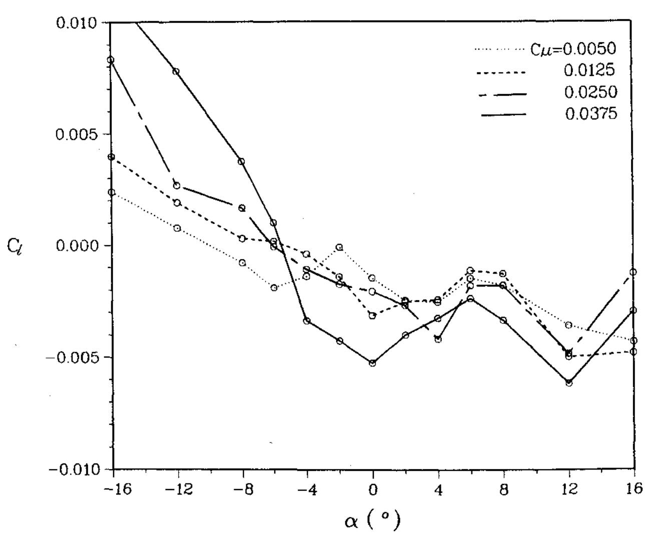

Fig. 16 Rolling moment coefficient, one-sided configuration.

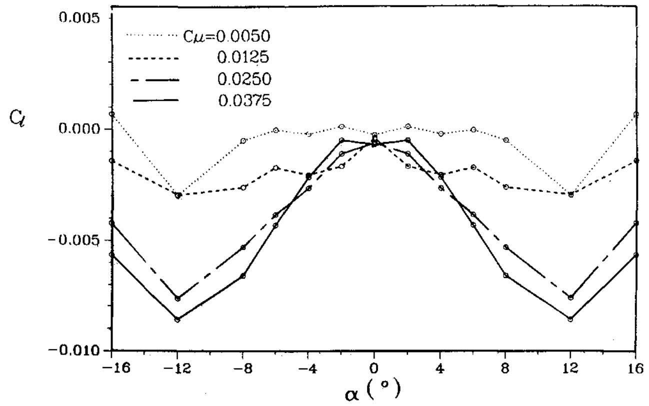

Fig. 17 Rolling moment coefficient, two-sided configuration.

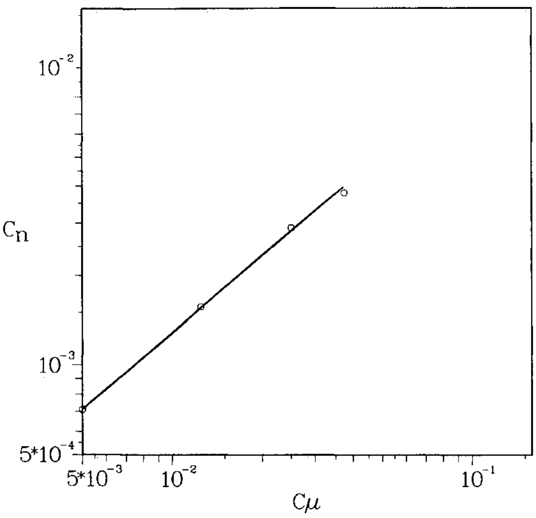

Fig. 18 Logarithmic plot.

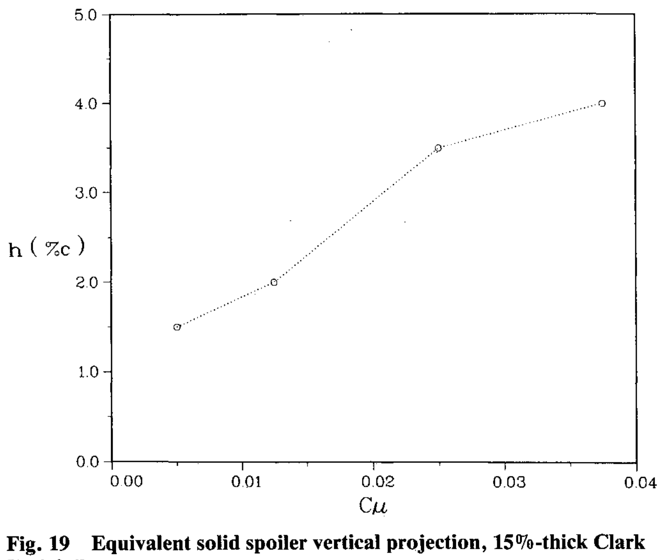

Fig. 19 Equivalent solid spoiler vertical projection, 15%-thick Clark Y airfoil.

periments reported in Ref. 11 were used. A straight wing of aspect ratio 4 with a 15%-thick Clark Y airfoil cross section was tested, fitted with spoiler on the upper surface, placed at the maximum thickness location, and covering 37.5% of the span. To compensate for the different aspect ratios of the two wings, the jet spoiler yawing moments were multiplied by the ratio 4/3.14. The comparison is still approximate since the two airfoils had different thicknesses, the Clark Y is not symmetrical, and the fraction of span covered by the solid spoiler is greater. In this comparison, the thickness aspect would make the jet spoiler look more effective than it actually is—as discussed below, it is expected that thick airfoils would respond better to the concept than thin ones—while the span extension would make it look less effective. For these reasons, the analysis is to be taken only as a rough indication of jet spoiler potential.

The solid spoiler was deflected by 60 deg with respect to the wing chord, and the lift coefficient of the case used in this comparison was 0.36. The lift coefficient is much less important in the jet spoiler than in the solid spoiler performance. In the case of the solid spoiler, both rolling and yawing moments increase with angle of attack, the rolling moment significantly faster. Figure 19 shows the vertical projection of the solid spoiler that would be required to equate the yawing and rolling moments produced by the one-sided jet spoiler for varying blowing intensity. The lower values of vertical projection in roll than in yaw are an indication of the substantially smaller coupling between roll and yaw in the jet spoiler case.

Conclusions

The jet spoiler concept has been explored at low subsonic speeds to examine its potential for generating yaw control aerodynamic forces with little lift penalty and reasonable roll coupling. Both one- and two-sided blowing configurations were tested. For the same jet momentum coefficient, which amounts to twice as much mass flow, the two-sided case showed less efficiency than the one-sided case.

The yawing moment arises from an increment of pressure upstream of the jet slot and a decrement downstream, resulting in a local increment in drag. The larger the vertical projection of the area on which the pressure induced by the jet spoiler acts, the greater the resulting yawing moment is expected to be.

The yawing moment produced by the one-sided jet spoiler is weakly dependent on angle of attack over a considerable range. In contrast, yawing and rolling moments produced by solid spoilers exhibit a marked dependence on angle of attack. Roll-yaw coupling is significantly weaker in the jet spoiler than in the solid spoiler case.

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