Alleviation of the Subsonic Pitch-Up of Delta Wings

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A "pylon vortex generator" concept has been proposed for alleviating the subsonic pitch-up instability of highly swept supersonic-cruise wings. Fixed at a part-span location, this leading-edge device utilizes the lateral velocity component in the flow approaching the swept wing to generate a streamwise vortex, rotating in a sense opposite to the normal leading-edge vortex. The resulting upwash reduction outboard of the device serves to delay the movement of the leading-edge vortex out of the tip regions with increasing angle of attack, thus improving the tip lift characteristics. Wind tunnel results on 60- and 74-deg flat-plate delta wings are presented to demonstrate the operation of the pylon vortex generator in modifying the spanwise leading-edge separation and vortex characteristics of the basic delta wings, resulting in effective pitch-up alleviation.

Nomenclature

A_{wet}	= wetted area
C_A	= axial (or chord) force coefficient
C_D	= drag coefficient
C_L	= lift coefficient
C_l	= rolling moment coefficient (body axis)
C_m	= pitching moment coefficient
C_N	= normal force coefficient
C_n	= yawing moment coefficient (body axis)
$C_{p_{L.E.}}$	= leading-edge pressure coefficient
α	= angle of attack
η	= fraction of semispan, distance from centerline

Introduction

THE renewed interest in supersonic-cruise projects in recent years has brought the subsonic aerodynamic problems of highly swept and slender wings to the fore. The specific problem addressed in this paper is that of pitch-up, viz., a nose-up change in the pitching moment with increasing lift, which generally leads to undesirable handling characteristics in maneuver and during approach and landing.

On wings of moderate sweep and aspect ratio, e.g., as employed on subsonic transport aircraft, pitch-up is well known to result from an abrupt trailing-edge stall of the tip sections. Slender wings in low-speed flight, on the other hand, are characterized by nearly full-span leading-edge separation, with vortex-induced lift dominating. In this instance, pitch-up occurs mainly from a progressive loss of vortex lift from the tip regions as the leading-edge vortices migrate inboard with increasing angle of attack. Depending on the leading-edge sweep angle, vortex breakdown also may occur, adding to the severity of pitch-up.

These different aerodynamic mechanisms naturally require different approaches toward pitch-up alleviation. Moderately swept wings frequently employ fences, snags, vortex generators, etc., which serve to arrest the spanwise boundary-layer flow into the tip regions, thus delaying the onset of tip stall. These boundary-layer control devices will be of little value, however, in dealing with leading-edge separation, where the use of leading-edge deflection or droop may be more appropriate. Unfortunately, the pronounced spanwise variation of upwash encountered on highly-swept low aspect ratio planforms requires a highly warped leading edge in order to ensure fully attached flow,[1] incorporating variable geometry to permit decambering for supersonic cruise. The leading-edge droop solution to the pitch-up problem of slender wings is thus burdened with practical drawbacks of mechanical complexity and attendant weight penalty.

As an alternative, the use of physically simple and lightweight but aerodynamically sophisticated devices on a cruise-optimized, fixed-geometry supersonic wing, accepting a small cruise drag penalty in return for considerably improved subsonic stability characteristics with a structurally simpler wing, may offer a better overall design solution. The first step in exploring such an alternative requires the demonstration of a suitable device concept capable of operating in a separated leading-edge flow environment. This paper reports preliminary investigations of a "pylon vortex generator" device which appears to combine the key requirements of physical simplicity and low drag with the desired aerodynamic effectiveness at high angles of attack. Wind tunnel force and pressure measurements with the device on 60- and 74-deg flat-plate delta wing models have been analyzed to assess the pitch-up alleviation capability and to delineate the basic flow phenomenon of the pylon vortex generator (PVG) concept.

Pylon Vortex Generator

The geometry and leading-edge location of the PVG, as well as its aerodynamic basis, are illustrated in Fig. 1. The device essentially consists of a vertically oriented, thin, sharp-edged blade projecting forward and downward from the wing leading edge, resembling a scaled-down pylon. One or more of these devices may be located at selected spanwise positions. The suggested aerodynamic mechanism of the PVG is as follows. The flow approaching the delta wing leading edge develops a sidewash component, whose incidence on the vertical PVG generates streamwise vortices from its swept edges. The lower vortex is relatively weak (coming off a shorter and more highly swept lower edge) and passes well below the wing, whereas the stronger upper vortex shed at the wing leading edge induces a reduction in the upwash on the outboard side, thereby promoting leading-edge flow attachment at an adjacent point. The wing leading-edge vortex is thus effectively locked and prevented from moving inboard of the PVG with increasing angle of attack, allowing vortex lift to persist over the tip regions, and so alleviating the pitch-

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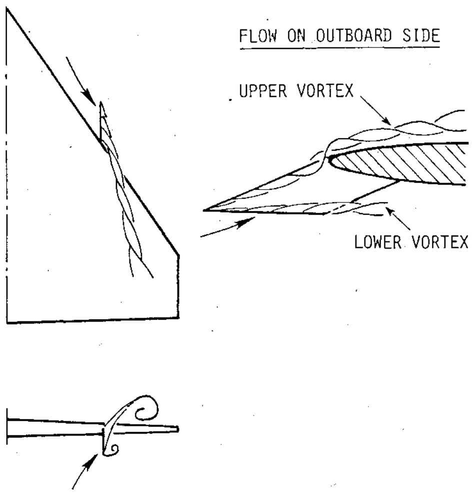

Fig. 1 Pylon vortex generator (PVG) concept.

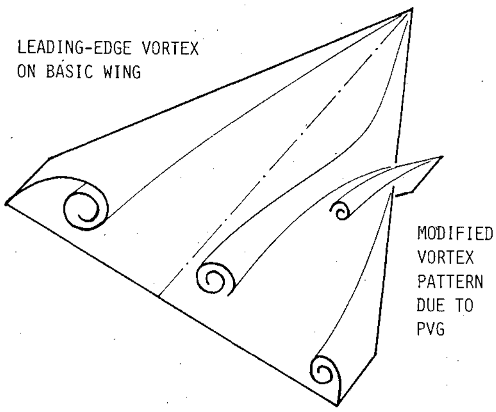

Fig. 2 Suggested vortex flow modification on delta wing due to PVG.

up tendency (Fig. 2). At low angles of attack in cruising flight the PVG will be inactive in the relatively weak sidewash, and only produce friction drag.

Preliminary smoke visualization trials in the NASA Langley 7- × 10-ft High Speed Tunnel with a PVG attached to an arrow wing model (of 71-deg leading-edge sweep, under test in a different program) validated the essentials of the PVG flowfield postulated above. A photograph showing the upper and lower vortex cores in a cross-flow plane just downstream of the PVG is presented in Fig. 3.

The aerodynamic "compartmentation" of the swept leading edge implied by the flow model of Fig. 2 may be extended by the use of additional PVGs suitably spaced across the wing span. A "compartmented" slender wing with multiple locked leading-edge vortices thus offers a novel approach toward tailoring the subsonic longitudinal characteristics, as opposed to variable geometry in pursuit of attached flow.

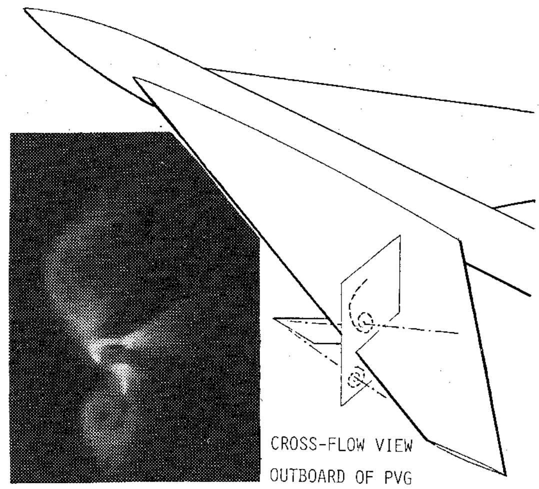

Fig. 3 Photograph of smoke visualization of PVG vortices on arrow wing model.

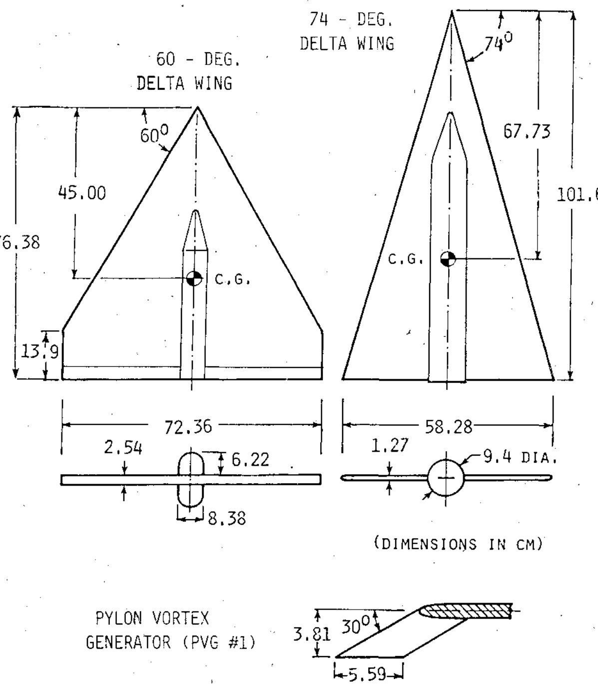

Fig. 4 Geometry and dimensions of delta wing test models and PVG.

Experimental Details

The geometry and principal dimensions of the test models and the leading-edge device are shown in Fig. 4. The delta wings were uncambered flat plates with blunt leading edges and beveled trailing edges. The 60-deg delta with semi-elliptical leading edges, a combined force and pressure model, was provided with a row of closely spaced static pressure orifices along the leading edge. The 74-deg delta wing force model had a semicircular leading-edge cross section. The tests were carried out in the NASA Langley 7- × 10-ft High Speed Tunnel at a nominal Mach number of 0.2 and Reynolds number of approximately 0.4×10^6 per m. Additional details regarding the models, equipment and test procedures, corrections, data reduction, etc., will be found in Refs. 2 and 3.

The PVG geometry was initially refined to a limited degree during tests described in Ref. 2, leading to the shape shown in Fig. 4 and referred to as PVG No. 1. Modifications of this shape were also tested as described in the next section. It should be noted that while PVG No. 1 incorporated a toe-in angle of 10 deg on the 60-deg delta tests, no toe-in was applied during tests with the 74-deg wing. It was found that while PVG toe-in (adopted to reduce the outward bending under aerodynamic load) had the effect of reducing the incremental drag at low angles of attack,[4] it did not influence the pitching-moment characteristics in any essential respect.

Discussion of Results

60-deg Delta Wing

The basic wing leading-edge separation characteristics will be considered first. Leading-edge pressure ($C_{P_{L.E.}}$) measurements provided a sensitive means of identifying the onset of leading-edge separation as a function of spanwise

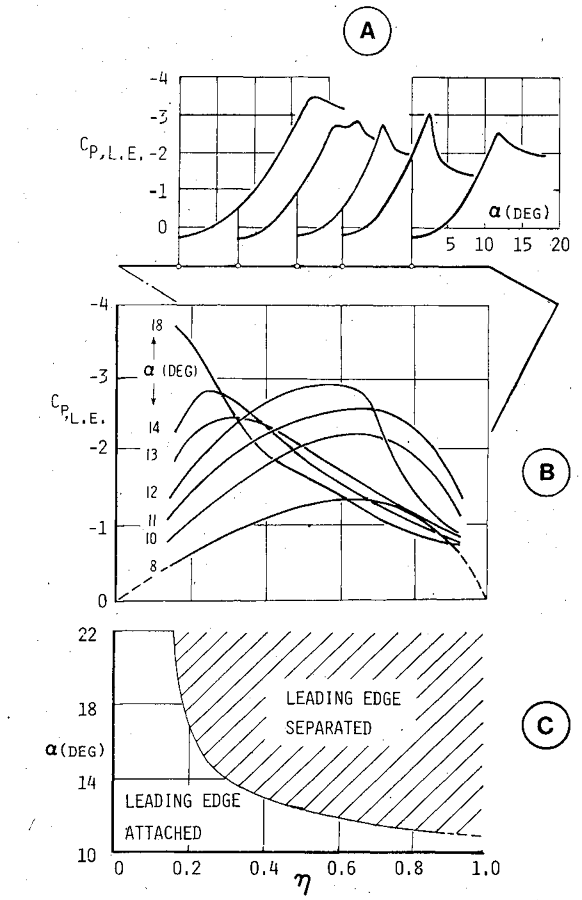

Fig. 5 Basic 60-deg delta wing leading-edge suction characteristics.

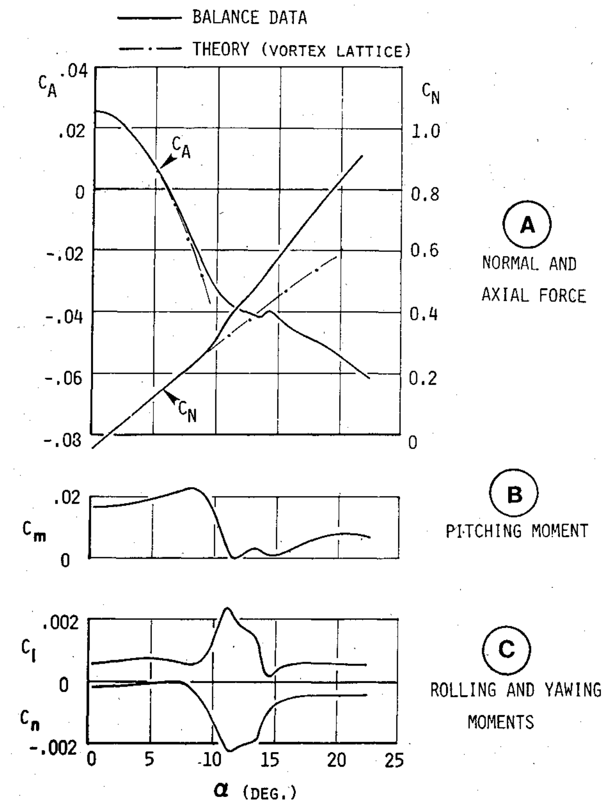

Fig. 6 Basic 60-deg delta wing aerodynamic coefficients.

distance and angle of attack; typical data from Ref. 3 are presented in Fig. 5. The $C_{P_{L.E.}}$ vs angle of attack (Fig. 5a) at several spanwise stations initially shows a quadratic increase of leading-edge suction until a $C_{P_{L.E.}}$ break occurs indicating the onset of separation. The spanwise $C_{P_{L.E.}}$ distributions (Fig. 5b) are convex-shaped, characteristic of attached flow up to $\alpha = 11$ deg, above which the suction levels in the outboard sections begin to collapse as leading-edge separation progresses inwards from the tip.

The spanwise influx of separation with increasing angle of attack is graphically depicted in Fig. 5c as a boundary dividing the separated (shaded) and attached-flow portions of the leading edge. Starting at about 10-deg angle of attack near the tip, separation moves rapidly to $\eta = 0.15$ at the highest angle of attack.

The basic-wing aerodynamic coefficients (Fig. 6) display noteworthy trends associated with the onset and development of leading-edge separation. The axial force, being particularly sensitive to the loss of leading-edge suction, starts to show the effects of separation around $\alpha = 9$ deg. Concurrently, the following trends appear in the remaining aerodynamic coefficients:

1) The normal force shows an upward break due to onset of vortex lift.

2) A sharp nose-down pitching moment indicates that the vortex lift is initially concentrated near the tips (due to the side-edge vortex of the cropped delta).

3) Rolling and yawing moments develop because of nonsymmetric development of the tip separations.

A further increase to $\alpha = 11$ deg brings about an abrupt pitch-up; according to Fig. 5c this occurs as leading-edge separation moves to $\eta = 0.6$. Since the C_N curve indicates a continued growth of vortex lift, the pitch-up must be attributed to a movement of the vortex lift out of the tip regions, as opposed to a vortex-breakdown effect. These observations on the basic wing would suggest that pitch-up might be alleviated by preventing leading-edge separation from moving inboard of $\eta \simeq 0.6$, which in turn indicates $\eta = 0.5$ as a suitable location for the PVG.

The aerodynamic coefficients with a PVG installed at $\eta = \pm 0.5$ are shown in Fig. 7, with the basic wing data (taken from Fig. 6) included as dashed curves for ease of comparison. It is at once apparent that the PVG has generally moderated the effects of leading-edge separation on the longitudinal as well as lateral characteristics. Of particular interest is the substantial relief noted in the pitch-up. The axial force data indicate that the collapse of leading-edge suction is considerably delayed, whereas the C_N curve still indicates some vortex lift. The inference is that the PVG did not basically affect the onset of leading-edge separation but restrained its spanwise growth to allow continued lift development outboard of the PVG to higher angles of attack.

The spanwise $C_{P_{L.E.}}$ distributions shown in Fig. 8 provide a direct indication of the leading-edge flow modification produced by the PVG located at $\eta = \pm 0.5$. The PVG effect on the leading-edge suction depends on whether the local flow was originally attached or separated; in the former case (represented by the $\alpha = 11$ deg data) the suctions immediately outboard of the PVG are reduced, whereas in the latter case ($\alpha = 16$ and 22 deg) they are increased in comparison with the basic wing. These opposite trends are both consistent with an effective reduction of the local angle of attack on the outboard side, in accordance with the postulated PVG flow mechanism. The observed decay of the PVG effect in inverse proportion to spanwise distance is characteristic of a streamwise vortex. According to the $C_{P_{L.E.}}$ data of Fig. 8, the PVG mechanism remained effective up to the highest angle of attack of the test (i.e., $\alpha = 22$ deg).

An example of the multiple-PVG effect on the spanwise leading-edge suction distribution is presented in Fig. 9 for the case of three equally spaced PVGs at $\eta = \pm 0.25$, ± 0.5, and ± 0.75. This result demonstrates the aerodynamic compartmentation effect referred to earlier. The associated improvement in the overall leading-edge suction results in

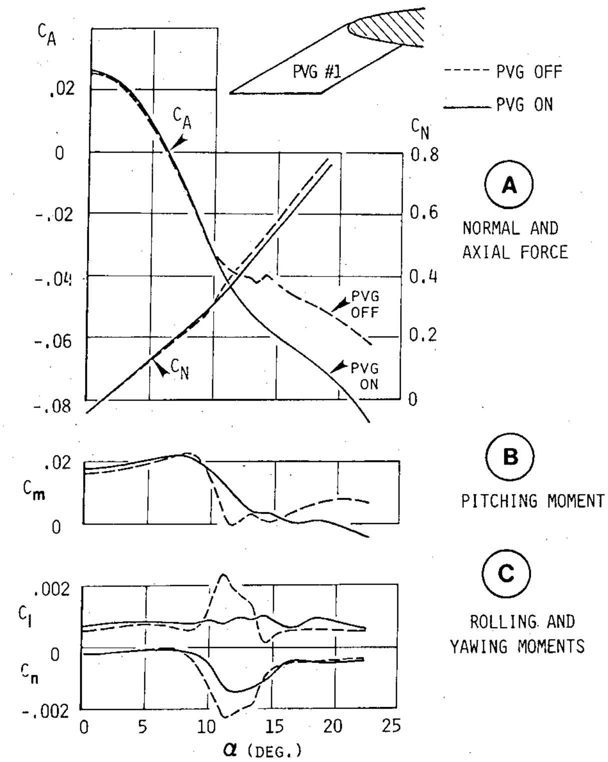

Fig. 7 60-deg delta wing aerodynamic coefficients as modified by a single pair of PVGs at $\eta = \pm 0.5$.

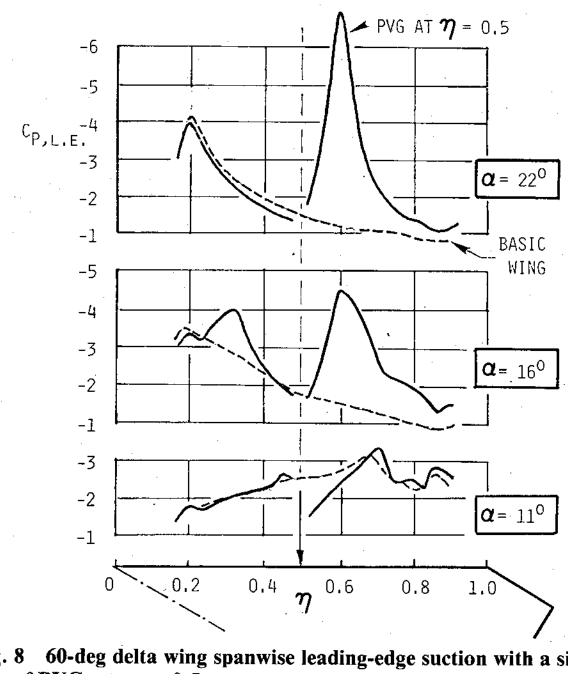

Fig. 8 60-deg delta wing spanwise leading-edge suction with a single pair of PVGs at $\eta = \pm 0.5$.

significant drag reduction at high angles of attack, inevitably at the cost of some vortex lift loss due to the attached-flow pockets produced along the leading edges (these aspects of the PVG performance have been discussed in Ref. 4).

Increasing the number of PVGs affects the pitching-moment characteristics as shown in Fig. 10, which includes results obtained with one, two and three pairs of PVGs, respectively, and also the basic wing (dashed) data for comparison. The pitch-up alleviation due to a single PVG pair at $\eta = \pm 0.5$ is reinforced by the addition of a second pair at $\eta = \pm 0.25$, leaving the low-lift portion of the C_m curve

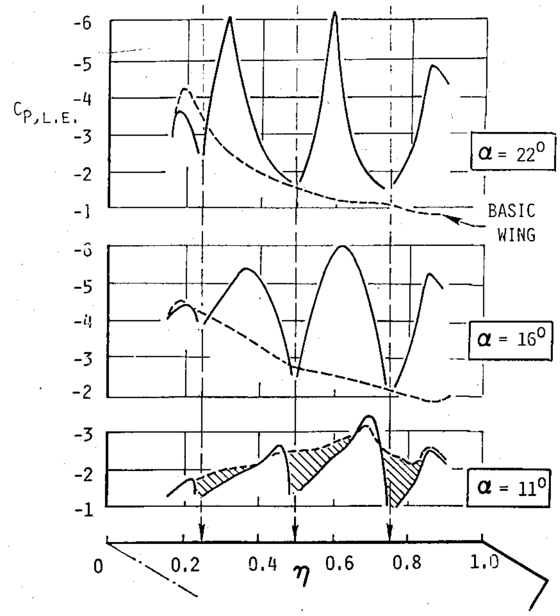

Fig. 9 60-deg delta wing spanwise leading-edge suction with three pairs of PVGs at $\eta = \pm 0.25$, ± 0.5, and ± 0.75.

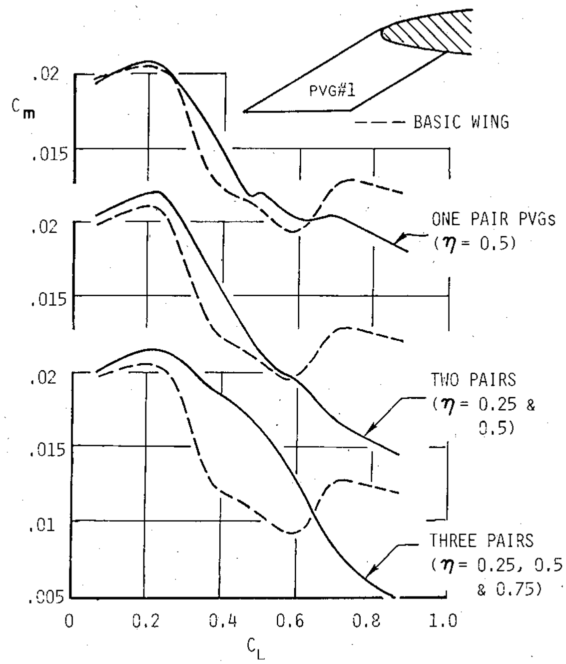

Fig. 10 Effect of multiple PVGs on 60-deg delta wing pitching-moment characteristics.

essentially unchanged. Adding yet a third PVG pair at $\eta = \pm 0.75$, however, mainly influences the low-lift portion, moderating the initial pitch-down presumably by delaying the growth of the cropped-tip separation, with little change at higher lift. The three-PVG arrangement thus produces a more linear and stable pitching-moment characteristic on this cropped delta; on a pure delta with pointed tips, a two-PVG system (i.e., at $\eta = \pm 0.25$ and ± 0.5) should be effective for pitch-up alleviation.

The influence of PVG geometry on its aerodynamic effectiveness will now be considered briefly for the case of a single-PVG installation at $\eta = \pm 0.5$. Systematic deviations from the standard PVG No. 1 shape were explored mainly in an effort to assess the relative importance of the upper and lower edges of the PVG. In the first series, the PVG height was reduced in two steps (PVG Nos. 2 and 3) as shown in Fig.

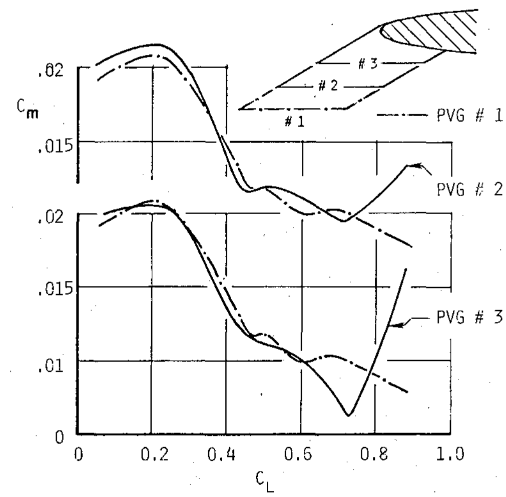

Fig. 11 Effect of PVG height reduction on 60-deg delta wing pitching-moment characteristics.

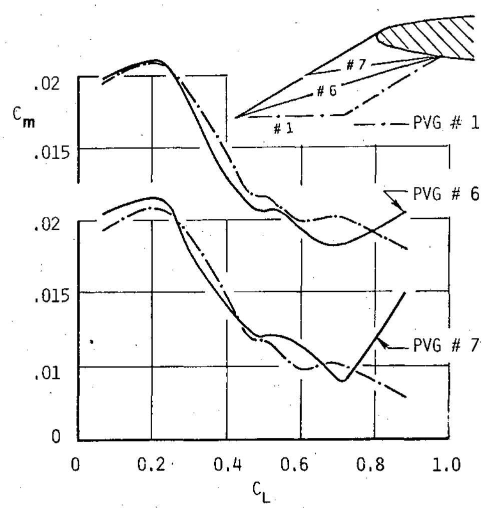

Fig. 12 Effect of PVG rear-edge modifications on 60-deg delta wing pitching-moment characteristics.

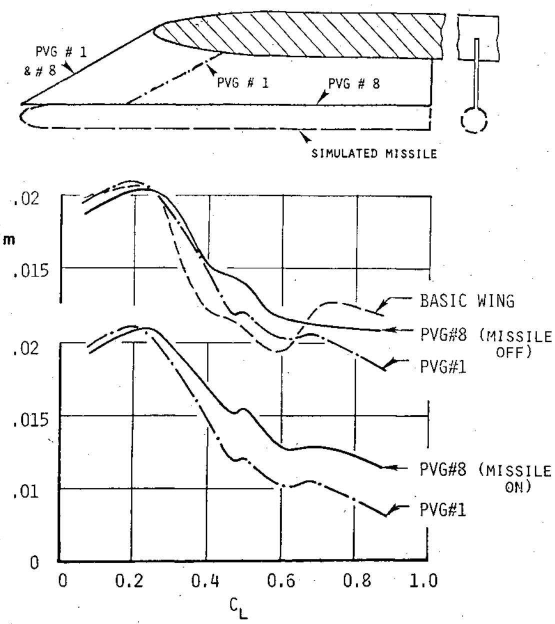

Fig. 13 Effect of PVG extension with and without simulated missile on 60-deg delta wing pitching-moment characteristics.

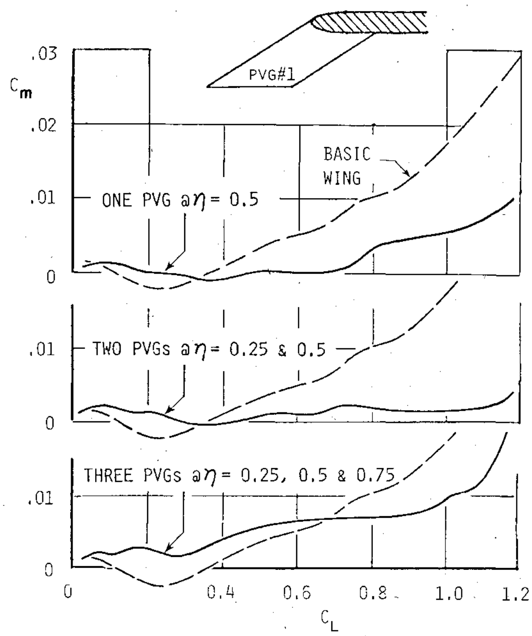

Fig. 14 Single and multiple PVG effects on 74-deg delta wing pitching-moment characteristics.

11, resulting in decreasing length of the upper edge with the lower-edge chord remaining constant. In the second series, the initially chordwise lower edge was cut back diagonally, first keeping the original upper edge and then halving its length (PVG Nos. 6 and 7, respectively, Fig. 12). The effect of these modifications was generally to degrade the pitch-up alleviation of the original PVG, i.e., to reduce the C_L for pitch-up, although an improvement still remained over the basic wing. In each case the loss of PVG effectiveness coincided with a collapse of the leading-edge suction outboard of the device; tuft visualizations indicated a simultaneous reversion to the single leading-edge vortex pattern of the basic wing.

The implied failure of the PVG mechanism was thought to be triggered by an earlier diversion of the counter-rotating lower vortex toward the wing leading edge as a result of the PVG cutback. This conjecture was investigated through an additional modification, consisting of an extension of the original PVG rearward under the wing which was expected to hold the lower vortex underneath the wing to a higher angle of attack. The resulting geometry (PVG No. 8, Fig. 13) also appeared to be of some practical interest, viz., as a means of imparting the PVG capability to missile-carrying pylons frequently employed on combat aircraft. Pitching-moment results with and without a full-length rod fixed to the extended lower edge (simulating a missile) are shown in Fig. 13. Without the rod, the stabilizing influence of PVG No. 8 is generally maintained except towards the highest angle of attack, whereas with the rod in position the entire pitching-moment curve of PVG No. 1 appears to be preserved with an overall nose-up rotation to account for the unstable contribution of the "missile." The shielding of the lower edge by the rod presumably suppressed the formation of the lower vortex. The results of Fig. 13 indicate, at least, that a store-carrying pylon at an appropriate spanwise location may be modified to serve the PVG aerodynamic function. On the whole, the PVG-shape studies tend to confirm that the upper vortex is crucial to its aerodynamic mechanism and indicate that keeping the lower vortex away from the leading edge may be important for continued effectiveness of the PVG at higher angles of attack.

74-deg Delta Wing

The results obtained with PVG applied to the 74-deg delta model will be briefly discussed. These results have been

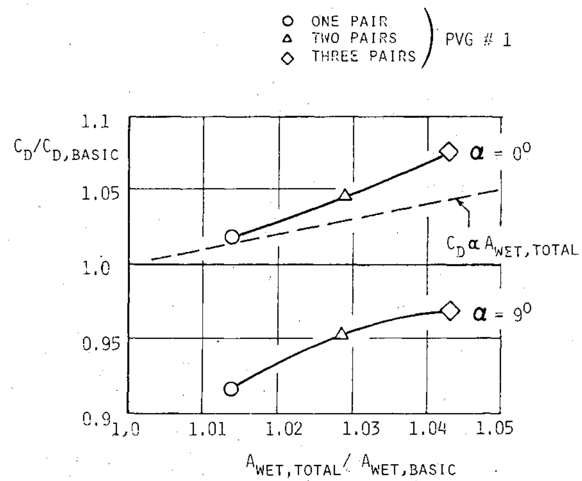

Fig. 15 Subsonic drag increment due to PVGs on 74-deg delta wing.

selected from the data documented in Ref. 2, mainly to demonstrate the performance of single and multiple arrangements of PVG No. 1. The pitching-moment characteristics are presented in Fig. 14. The basic wing, represented by dashed curve, displays a pitch-up at $C_L = 0.25$ approximately. A pair of PVGs installed at $\eta = \pm 0.5$ delay the pitch-up to $C_L = 0.7$. Adding a second pair of PVGs at $\eta = \pm 0.25$ postpones the pitch-up almost to $C_L = 1.1$ (or $\alpha = 30$ deg). The forward PVGs evidently contribute by retarding the vortex lift development ahead of the c.g., which in combination with sustained vortex lift in the tip regions due to the midspan PVGs, controls the center-of-pressure movement over a larger C_L range. The effect of adding a third pair of PVGs at $\eta = \pm 0.75$ appears mainly to introduce an overall unstable slope in the pitching-moment curve as compared to the two-PVG arrangement—an expected consequence of reduced lift near the tips due to the proximity of the aft PVG pair. Thus a two-PVG installation at $\eta = \pm 0.25$ and ± 0.5, again is found optimum for pitch-up alleviation, just as in case of the 60-deg delta.

Finally, a consideration of the drag increment due to the PVGs on the 74-deg delta is in order. Since the drag penalty at cruise lift coefficients is likely to arise mainly from skin friction on the added wetted area of the device, the available subsonic drag data provide a useful guide; the wave-drag contribution of the PVG is expected to be small in view of its geometrical features, e.g., small thickness ratio, high sweep, sharp edges, and pointed apex, as well as the small relative size. The subsonic drag relative to the basic wing drag is plotted vs the wetted area ratio in Fig. 15. The zero-lift drag increment is seen to be essentially due to skin friction (allowing for the higher average PVG-skin-friction coefficient in comparison with the basic wing due to the large Reynolds number difference.) The data for $\alpha = 9$ deg (corresponding to $C_L = 0.3$) also plotted in Fig. 15 show the significant drag reduction due to leading-edge suction improvement by adding the PVGs; the wetted area effect remains similar to that observed in the zero-lift drag data.

Concluding Remarks

A pylon vortex generator (PVG) concept has been proposed for alleviating the subsonic pitch-up of highly swept supersonic-cruise configurations. Exploratory wind-tunnel investigations on 60- and 74-deg flat-plate delta wing models validated the concept and its postulated aerodynamic basis. The use of multiple PVGs in a suitable spanwise arrangement was highly effective in pitch-up control at the cost of only skin-friction drag increment. Because of the small size of the device and its low-drag shape, the supersonic drag penalty is expected to be minor.

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