AIAA JOURNAL
Vol. 45, No. 1, January 2007

Control of Vortex Breakdown over a Delta Wing Using Forebody Slot Blowing

Y. D. Cui,* T. T. Lim,† and H. M. Tsai‡
National University of Singapore, Singapore 117508, Republic of Singapore

DOI: 10.2514/1.22575

In this paper we study the effectiveness of forebody slot blowing to control vortex breakdown over a generic delta wing-body configuration. The motivation is to exploit the benefits of both slot blowing and canards to control vortex breakdown over a delta wing. Parameters investigated include slot length, slot width, single and double-sided blowing, and the Reynolds number. Time-averaged flow images show that Reynolds number has little effect on vortex breakdown location, at least for the range of conditions studied here, and a single-sided blowing has favorable effects on the blowing side and unfavorable effects on the nonblowing side. It is postulated that when fluid is discharged from the slot at the forebody in the spanwise direction, it produces a vortex sheet that interacts with the freestream and is rolled up to form a trailing vortex further downstream. The rolled-up vortex sheet produces a downwash effect on the blowing side and a sideslip effect on the opposite side. The downwash modifies the flowfield around the leading edge of the wing, causing a delay in vortex breakdown. To compensate for the unfavorable effects of blowing on the opposite side, a much higher blowing momentum (more than two times the single-sided slot case) is needed to delay vortex breakdown on both sides of the wing when double-sided blowing is employed. Our results also show that for a given Reynolds number and angle of attack, increasing the blowing momentum leads to a substantial delay in the vortex breakdown position. In addition, for the same blowing momentum coefficient, varying the slot width has little effect on the breakdown location, whereas increasing the slot length has favorable effect, particularly at lower angles of attack.

Nomenclature

A_j	=	slot area
AOA	=	angle of attack
c	=	root chord
C_m	=	blowing momentum coefficient, $\rho Q^2/(A_j qS)$
f	=	oscillating frequency of the vortex breakdown location
Q	=	volume flow rate of blowing
Re	=	Reynolds number, Uc/v
S	=	area of the delta wing
SL	=	slot length
U	=	freestream velocity
V_j	=	average slot exit velocity
Vr	=	velocity ratio, V_j/U
W	=	slot width
X_b	=	vortex breakdown position from the apex of the wing
$X_{b\mathrm{mean}}$	=	mean vortex breakdown position
v	=	kinematic viscosity of water

I. Introduction

DELTA-WING configuration has been used extensively in modern fighter aircraft because of its efficiency in high-speed flight, plus the advantage of additional vortex lift at moderate angle of attack [1–3]. However, when the angle of attack is increased beyond a certain value, a phenomenon commonly referred to as vortex breakdown (or vortex burst) is produced over the wing. This phenomenon is characterized by an abrupt change in the structure of the vortex core following a sudden deceleration of its axial velocity component. The presence of vortex breakdown can have detrimental effects on not only the aerodynamic characteristics of the wing, such as a reduction in lift, an increase in drag, and changes in moment characteristics, but also heightened structural fatigue due to strong pressure fluctuations, unsteadiness, and vibrations. Hence, the overall aircraft's performance, controllability, and maneuverability can be severely affected. Since it was first discovered by Peckham and Atkinson [1] in 1957, the vortex breakdown phenomenon has been studied extensively by many researchers. Although some inroad has been made in the understanding of the flow phenomenon, much remains unclear, as indicated in the review articles by Hall [4], Leibovich [5], Escudier [6], Délery [7], Althaus et al. [8], and, more recently, by Lucca-Negro and O'Doherty [9]. Although complete understanding of the flow phenomenon still eludes researchers, the need to manage vortex breakdown over a delta wing at high angles of attack has, over the years, led many to propose a wide range of flow control techniques (see Mitchell and Délery [10]) and devices such as leading-edge flaps [11–14], apex fences [15], or even blowing and suction in the tangential direction along a rounded leading edge [16,17], and suction near the separation point [18–20]. It is generally agreed that trailing-edge blowing [21–26] or suction [27] techniques delay vortex breakdown by altering the downstream pressure gradient, and the along-core blowing technique [28–32] delays vortex breakdown by increasing the axial velocity (i.e., a reduction in the swirl number). Although there are many other blowing/suction techniques, including different blowing/suction locations and orientations, they all function more or less the same way. Dixon [33] believed that spanwise blowing (SWB) on the wing provides sweeplike effects as the SWB jets are entrained in the leading-edge vortices. Bradley and Wray [34] credited the success of their blowing technique to the increase in the vortex stability, which to some extent is related to the longitudinal flow in the vortex core.

In addition to the preceding techniques, passive devices such as canards, strakes, leading-edge extensions (LEXs), and double-delta wings [35–43] have also been applied in numerous aircraft. These devices control vortex breakdown by modifying the flowfield and inducing a nonuniform distribution of local angles of attack at the wing, leading to the generation of a nonconical vortex formation and

Received 19 January 2006; revision received 31 July 2006; accepted for publication 22 October 2006.

*Associate Scientist, Temasek Laboratories, 5 Sports Drive 2.
†Associate Professor, Department of Mechanical Engineering, 9 Engineering Drive 1, Singapore 117576.
‡Principal Research Scientist, Temasek Laboratories, 5 Sports Drive 2. Member AIAA.

the corresponding delay in the vortex breakdown over the wing [37,39,42].

Depending on the operating conditions, some control devices function better than others. In the present investigation, we build upon the knowledge gained from earlier studies of vortex breakdown control techniques/devices and propose a control method that we believe exploits the benefits of both the slot blowing and the effectiveness of canards that are often used to control vortex breakdown over a delta wing. The proposed technique involves applying spanwise slot blowing at the forebody part of a generic delta wing-body configuration, and it is anticipated that the interaction of the forebody blowing and the freestream leads to a generation of a virtual canard effect. As far as we are aware, this technique has not been previously reported, although earlier studies with blowing over the canard and wing [44] and at the leading-edge extension [45] show the potential of this technique in delaying vortex breakdown.

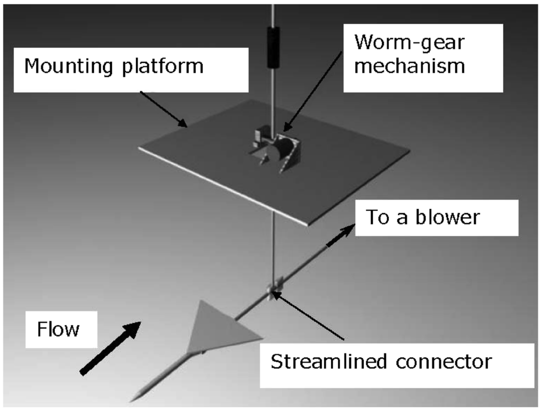


Fig. 2 Schematics of the model and the support system.

II. Experimental Setup

The experiments were conducted in the water channel facility located in the Temasek Laboratories of the National University of Singapore. The test section of the water channel measures 1-m high (height of the water surface), 0.75-m wide, and 2.25-m long. It is surrounded by tempered glass on the two sides and at the bottom, which allows high-quality flow visualization from almost any angle. Although the water channel can achieve a maximum velocity of 0.9 m/s in the test section with a corresponding turbulence intensity of less than 1%, the speed selected for the present study ranged from 15.5 to 29.1 cm/s.

Because the aim of the present investigation is to assess the effectiveness of forebody slot blowing, a generic delta wing-body configuration model was used (see Fig. 1). The delta wing has a sweep angle of 60-deg, root chord length of 248 mm, thickness of 5 mm, and was fabricated from marine-grade aluminum plate. The leading edges of the wing are beveled at 45 deg on the windward sides. The forebody was fabricated from a hollow cylindrical brass tube of 22-mm o.d. (D) and 10-mm i.d., with a tangent ogive tip with a fineness ratio of 1.5. The ogive tip was located 6.72 D upstream of the apex of the wing and sufficiently far way so that its tip vortices had minimal influence on the flowfield around the wing. The hollow cavity served as a chamber from which the blowing fluid was ejected. The blowing slots with rectangular shape were machined at the center plane of the forebody cylinder and parallel to the wing, and each has a predetermined length of 20, 30, and 40 mm and width of 0.3, 0.5, and 0.8 mm, respectively. The tube connected to the forebody also functioned as a supporting sting to which a flowmeter was connected to measure the blowing flow rate. A schematic drawing of the model and the supporting structures are shown in Fig. 2. The angle of attack of the model was controlled by a worm-gear system driven by a stepper motor, with the error of less than 0.5 deg. No side slip or roll angle were considered in the present investigations and, therefore, these angles were set to zero, with careful attention to ensure flow symmetry. Four reference lines parallel to the trailing edge were marked on the delta wing for the purpose of identifying the vortex breakdown position.

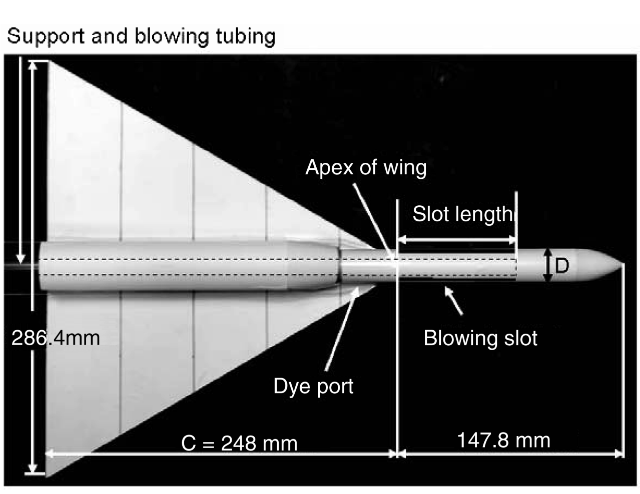


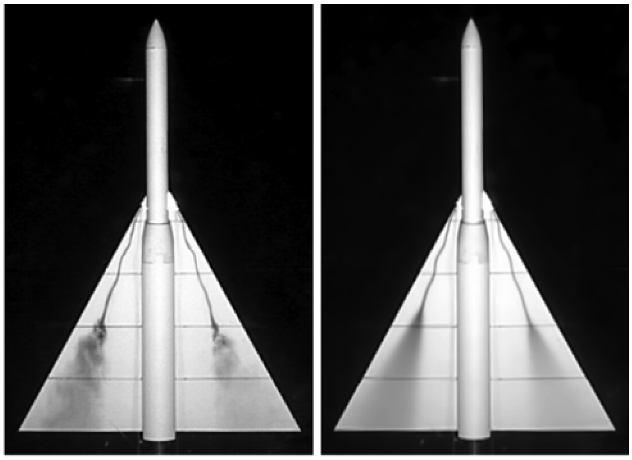
Fig. 1 Generic delta wing-body model with a 60-deg sweep angle.

To visualize the flow, a mixture of food dye and water (diluted with alcohol to achieve the specific gravity of approximately one) was released slowly through the dye ports made of stainless steel tubing embedded in the model. The flow rate of the dye was regulated by miniature valves to minimize flow interference, and in all cases, flow images were captured by a CCD video camera for subsequently analysis.

The Reynolds number, based on the root chord length and the freestream velocity, ranged from 4.5×10^4 to 8.5×10^4. The effect of slot blowing is quantified by a common parameter called the blowing momentum coefficient, which is defined as $C_m = \rho Q^2/(A_j qS)$, where q is the dynamic pressure of the freestream, ρ is the density of the blowing fluid, and Q is through one slot for a single-sided blowing and two slots for double-sided blowing.

III. Results and Discussions

Before discussing the results, a brief description is given here of how vortex breakdown location is determined. Under steady conditions, the vortex breakdown location is normally ascertained by identifying the point at which the vortex core suddenly expands. However, the vortex breakdown over a delta wing is anything but steady. It exhibits strong fluctuations along the axes of the vortices, sometimes up to 10% of the chord length [46–48], and this makes precise measurement of the location of the vortex breakdown difficult. To circumvent this problem, time-averaged images are used to determine the mean breakdown location, using a MATLAB code on a time series of the captured video images. A previous study by Menke et al. [48] shows that the dimensionless frequencies of vortex oscillating (fc/U) is approximately less than 0.2. To ensure that the sequence of images selected is five times longer than the period of oscillating of the breakdown location, 512 or 1024 frames (20.48 or 40.96 s in time) were used for the analysis. Figure 3 shows two images at the same experimental conditions, one instantaneous and the other time-averaged images. The vortex breakdown position was located with Photo Editor software by detecting the pixel position at which the dye suddenly expands in the time-averaged image. In Fig. 3, the portside vortex breakdown location is measured to be 0.57 c from the apex of the wing for Fig. 3a and 0.54 c for Fig. 3b. Because the breakdown locations at the portside and the starboard side of the wing exhibited a small degree of asymmetry, the mean breakdown location (averaged of the portside and starboard side breakdown locations) was used for double-sided blowing for the purpose of comparison only. However, in the case of a single-sided blowing, the breakdown locations at the portside and the starboard were considered individually. In addition, to support our assertion that the ogive tip vortices have no influence on the preceding results,



a) b)

Fig. 3 Comparison between a) instantaneous image and b) time-averaged image at AOA = 20 deg and $Re = 4.5 \times 10^4$. Note that 1024 frames were used to obtained Fig. 3b.

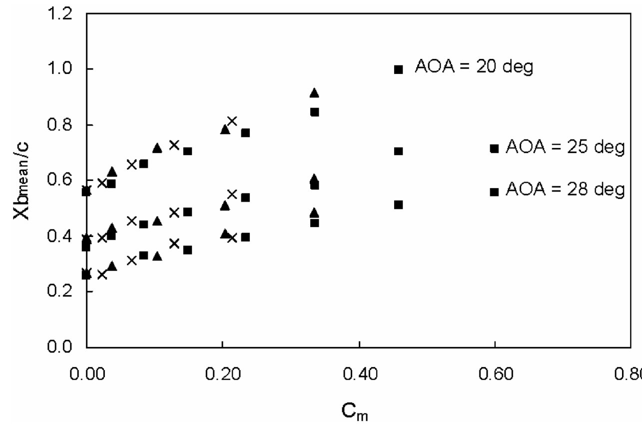


Fig. 5 Vortex breakdown location vs blowing momentum coefficient at angles of attack of 20, 25, and 28 deg for three Reynolds numbers (■ for $Re = 4.5 \times 10^4$, ▲ for $Re = 6.8 \times 10^4$, and × for $Re = 8.5 \times 10^4$).

experiments were repeated for different distances between the ogive tip and wing tip, and similar results were obtained.

A. Double-Sided Forebody Slot Blowing

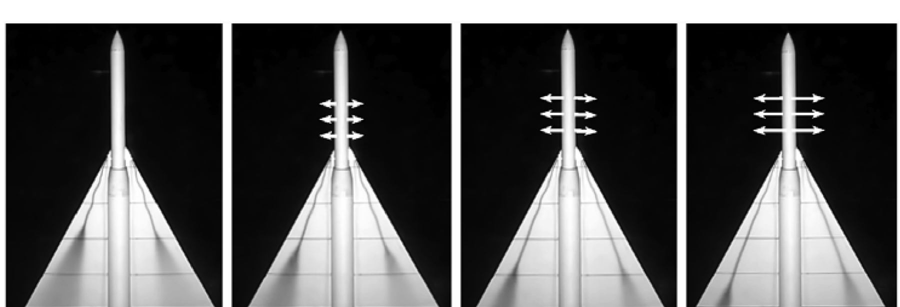
This part of the investigation was first conducted using a rectangular slot 40-mm long and 0.5-mm wide, with one end of the slot coinciding with the wing apex in the streamwise direction. For the purpose of comparison with the other slot configurations, this arrangement is referred to as a basic configuration. Figure 4 shows the time-averaged flow images for double-sided blowing for AOA = 20 deg and $U = 15.5$ cm/s ($Re = 4.5 \times 10^4$). It can be seen that with no blowing, the mean vortex breakdown location occurred at about 0.54 c (close to the second line from the trailing edge), and there was a slight asymmetry between the two breakdown locations. However, when a small blowing momentum of $C_m = 0.084$ is applied, there is a noticeable delay in the breakdown locations (Fig. 4b), and further increases in the blowing momentum lead to additional delays in the breakdown location, as can be seen in Figs. 4c and 4d. As pointed out earlier, due to the slight asymmetry in the breakdown positions, and for the purpose of comparison with other flow conditions, a mean vortex breakdown location was used to evaluate the overall effects of the double-sided slot blowing.

Experiments were also conducted at AOA = 20, 25, and 28 deg with $U = 15.5$ cm/s, 23.3 cm/s, and 29.1 cm/s (correspondingly, $Re = 4.5 \times 10^4$, 6.8×10^4, and 8.5×10^4), and the results are presented in Fig. 5. It is well known that the Reynolds number has virtually no effect on the separated flow (from the sharp leading-edge delta wing) that gave rise to the intense vortices forming above a delta wing. This is true of our experimental results, which show that the Reynolds number has little effect on the breakdown location for the same blowing momentum coefficient and angle of attack; the same cannot be said about the magnitude of the blowing. In fact, at $C_m = 0.2$, approximately 20% c delay was realized for a 20-deg angle of attack, 15% c for 25 deg, and 14% c for 28 deg. However, when C_m is increased to 0.4, the corresponding delays for the three angles of attack were 35, 20, and 20% c, which show that a higher momentum fluid is more effective in delaying vortex breakdown, at least for the range of conditions investigated here.

The encouraging results previously obtained raise the questions of how the slot length and the slot width would influence the breakdown location, and if the blowing on one side affects the flow behavior on the opposite side. To answer these questions, we decided to carry out further experiments, and the results are presented next.

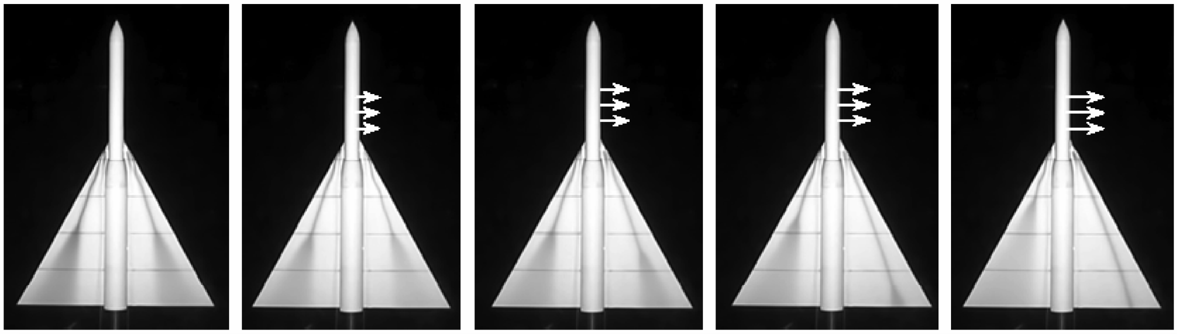
B. Single-Sided Forebody Slot Blowing

Single-sided blowing was realized by blocking one of the side blowing slots, and typical flow visualization results under this condition are presented in Fig. 6 for the starboard side blowing at AOA = 20 deg and $Re = 6.8 \times 10^4$. It can be seen from the figure that for a small momentum coefficient ($C_m = 0.034$), although breakdown location at the starboard side was delayed, the one at the portside was not affected significantly. In contrast, increasing C_m to 0.052 and 0.074 leads to a significant delay in the breakdown position at the starboard side and the promotion of vortex breakdown at the portside (see Figs. 6d and 6e). These results are plotted in Fig. 7 for AOA = 20 and 25 deg, and $Re = 6.8 \times 10^4$, which clearly show that a single slot blowing has favorable effects on the blowing side and unfavorable effects on the nonblowing side. This unexpected behavior can be used favorably to provide an additional roll control. It is also of interest to note that for AOA = 20 deg at about $C_m = 0.062$, the breakdown location was delayed till almost the trailing edge for a single-sided blowing (see Fig. 7), and for double-sided blowing (Fig. 5), $C_m = 0.42$ (for individual slot $C_m = 0.21$)



a) Cm = 0.0 b) Cm = 0.084 c) Cm = 0.234 d) Cm = 0.338

Fig. 4 Time-averaged images of vortex breakdown structures for different blowing momentum coefficients for double-sided blowing (SL = 40 mm and $W = 0.5$ mm) at AOA = 20 deg and $Re = 4.5 \times 10^4$. Arrows indicate the direction of forebody slot blowing.



a) Cm = 0.0 b) Cm = 0.018 c) Cm = 0.034 d) Cm = 0.052 e) Cm = 0.074

Fig. 6 Time-averaged images of vortex breakdown structures vs blowing momentum coefficient for a single-sided blowing (SL = 40 mm and $W = 0.5$ mm) at AOA = 20 deg and $Re = 6.8 \times 10^4$. Arrows indicate the direction of forebody slot blowing.

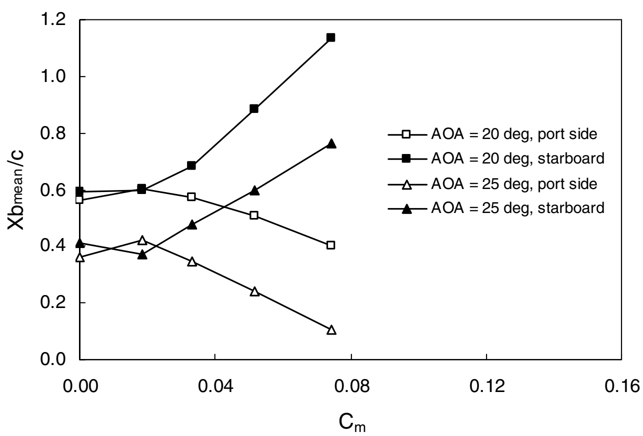


Fig. 7 Changes in the vortex breakdown positions with blowing momentum coefficient by starboard blowing only, at $Re = 6.8 \times 10^4$.

was needed to achieve the same result. This finding suggests that in order to compensate for the blowing having an unfavorable effect on the opposite side, a much higher blowing momentum is needed to provide a similar delay in the breakdown locations for the double-sided blowing.

Mitchell et al. [25] presented results of a 75-deg sweep angle delta wing in a water tunnel with symmetric (i.e., double-sided) and asymmetric (i.e., single-sided) trailing-edge blowing to control vortex breakdown. Their results showed that asymmetric blowing promoted early vortex breakdown of the uncontrolled vortex, which is consistent with our results for a single-sided blowing. They postulated that "the asymmetric blowing blocks the flow on the side where it is applied, and as a result, the flow works its way to the other side." Mitchell et al. [32] also studied vortex breakdown over 70-deg sweep angles on a delta wing model using asymmetry (single-sided) portside along-core blowing. Their results showed the ability of the technique to displace the portside vortex breakdown location by more than 20% of the chord at various test conditions, and in contrast, the mean starboard vortex breakdown location deteriorated and shifted farther upstream. They believed that "the asymmetry flow control influences both the controlled and uncontrolled leading-edge vortices, denoting an interaction between the two leading-edge vortices."

In our experiments, it was also observed that at higher blowing momentum coefficient, the dye at the nonblowing side is attracted to the blowing side. This unfavorable effect on the uncontrolled side could be due to the higher momentum of the ejected fluid generating a low-pressure area and produces a sideslip on the freestream on the opposite side, consequently, promoting vortex breakdown by reducing the effective sweep angle. This is further clarified by a sketch shown in Fig. 8, which depicts the effect of a single-sided blowing on the main flow and how it leads to delaying vortex breakdown on the blowing side, due to favorable downwash and

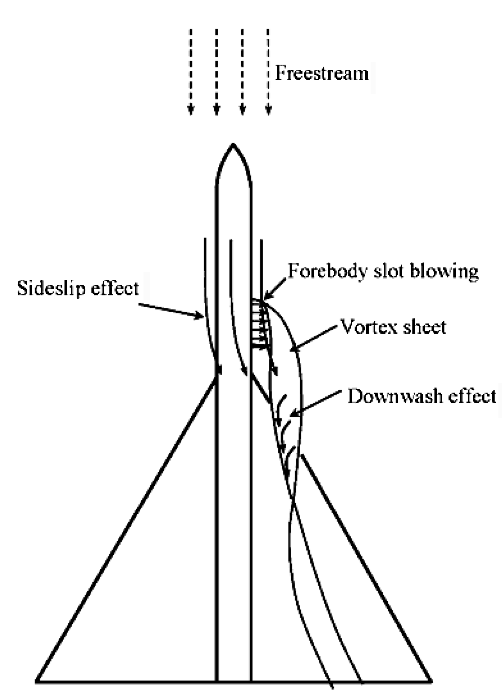


Fig. 8 Sketch of sideslip and downwash effects of a single-sided blowing on the flowfield.

sideslip effects, and promoting vortex breakdown on the other side, due to unfavorable sideslip effect.

Figure 9 is a typical picture showing a side view of a single-sided blowing (i.e., portside blowing) at AOA = 20 deg and $Re = 6.8 \times 10^4$ with $C_m = 0.052$. Here, the blowing fluid was mixed with dye for visualizing purposes, and the results show how the ejected sheet of fluid interacted with the incoming flow before rolling up further

Fig. 9 A side view image showing a single-sided blowing at AOA = 20 deg, $Re = 6.8 \times 10^4$, and $C_m = 0.052$.

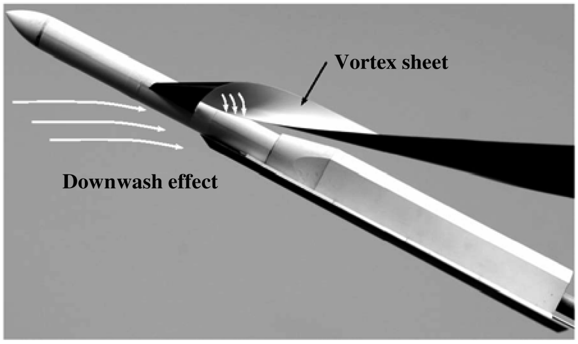


Fig. 10 Sketch of side view of the downwash effect of the forebody slot blowing.

downstream. Although the flow behavior could be seen with the naked eye, rapid diffusion of dye reduces the quality of the visualization. To illustrate it more clearly, a sketch of the downwash effect of the forebody slot blowing is shown in Fig. 10.

C. Comparison with the Effects of Canards on Vortex Breakdown Location

We have postulated earlier that the sheet of fluid ejected from the slot interacts with the incoming flow and produces the effect of a virtual canard. To support our postulation, an experiment was carried out in which we compare the effect of forebody slot blowing with that of canards. The canards were chosen to fit the slot, and each has a chord length of 40 mm, a thickness of 0.8 mm, and a sweep angle of 65 deg. Figure 11 shows the time-averaged results at AOA $= 20$ deg and $Re = 6.8 \times 10^4$ for the three different arrangements, namely, a basic configuration, a basic configuration with canards, and a basic configuration with forebody slot blowing. It can be seen that both the canards and the slot blowing ($C_m = 0.2$) configurations are able to delay vortex breakdown locations (see Figs. 11b and 11c), but the trailing vortices from the canards appeared to have trajectories slightly closer to the centerline of the body. This may be due to the stronger vortices generated by the canard interacting with the separated vortices. It is well known that canards delay vortex breakdown over the wing by modifying the flowfield and inducing a nonuniform distribution of local angles of attack at the wing, leading to the generation of a nonconical vortex formation [37,39,42]. From the preceding results, it could be postulated that forebody slot blowing produces a similar virtual canard effect in that the freestream interacts with the ejected vortex sheet, causing it to roll up further downstream. At the same time, the freestream is deflected by the presence of the rolled-up vortex sheet to produce a downwash effect, which could modify the flowfield around the leading edge of the wing, leading to a delay in breakdown position. To illustrate the comparison of the two techniques, a sketch showing the effect of

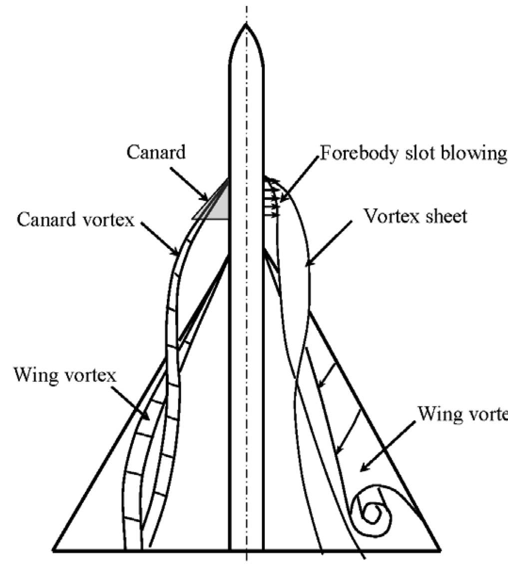


Fig. 12 Sketch of the effects of a canard and forebody slot blowing on the flowfield. (The canard effect was drawn according to the sketch of Tu [40]).

canard and forebody slot blowing on the flowfields is shown in Fig. 12. For ease of comparison, the effects of a canard and forebody slot blowing on the flowfield are sketched on the left and right side of a delta wing, respectively.

D. Effects of Slot Length on Vortex Breakdown Location

In this section, we present results of the experiments conducted to study the influence of the slot length on vortex breakdown location. Three slot lengths with SL $= 20$, 30, and 40 mm were selected, and the width of the slot was kept constant at 0.5 mm. Figure 13 shows the results for AOA $= 20$ and 25 deg with $Re = 4.5 \times 10^4$. It can be seen that for a given blowing momentum coefficient, the longer slot length appears to have favorable effect on the breakdown position, however, the effect decreases with higher angle of attack. Here, it is likely that the longer slot generates more downwash, which produces favorable results. The same behavior is also observed for a higher Reynolds number of $Re = 6.8 \times 10^4$ (Fig. 14).

E. Effects of Slot Width on Vortex Breakdown Location

In this case, three slot widths of $W = 0.3$, 0.5, and 0.8 mm were tested, and the slot length was kept constant at 40 mm. Figure 15 shows the results obtained for AOA $= 20$ and 25 deg under $Re = 4.5 \times 10^4$. Here, it can be seen that for a given momentum coefficient and angle of attack, the slot width does not have

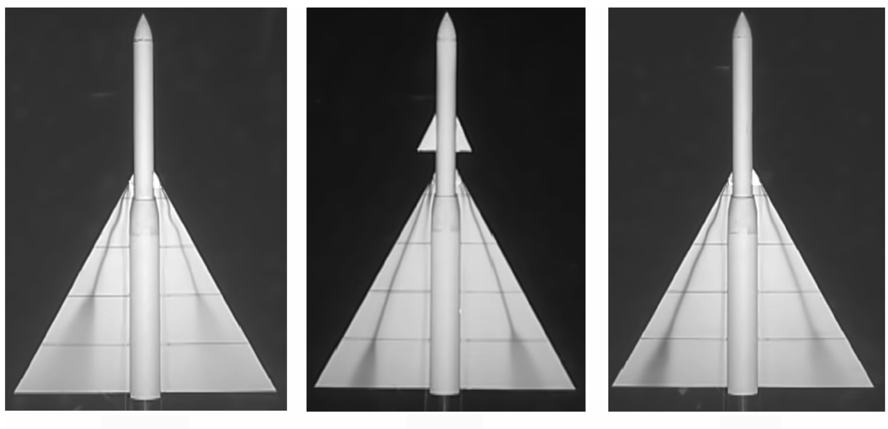


Fig. 11 Effects of canards and double-sided forebody slot blowing on the vortex breakdown location at AOA $= 20$ deg and $Re = 6.8 \times 10^4$ for a) basic configuration, b) basic configuration with canards, and c) basic configuration with double-sided slot blowing at $C_m = 0.2$.

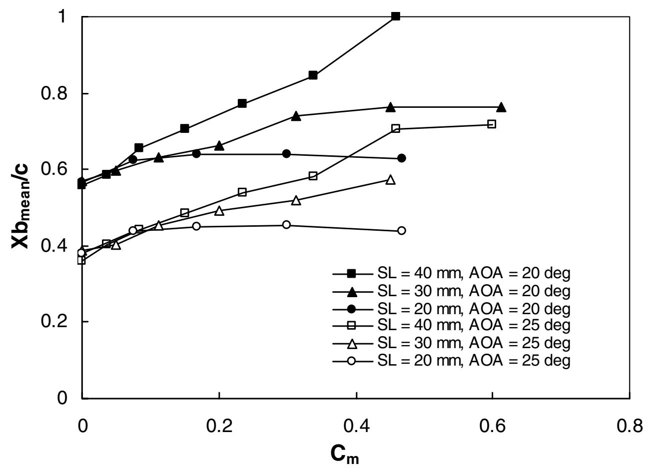


Fig. 13 Vortex breakdown location vs blowing momentum coefficient for different slot lengths at $Re = 4.5 \times 10^4$.

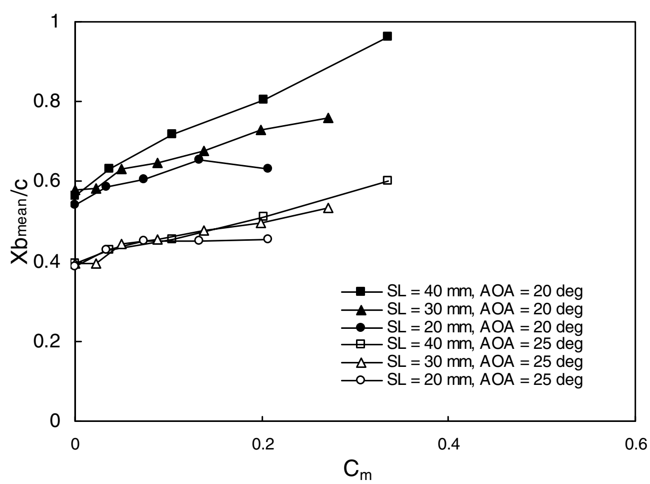


Fig. 14 Vortex breakdown location vs blowing momentum coefficient for different slot lengths at $Re = 6.8 \times 10^4$.

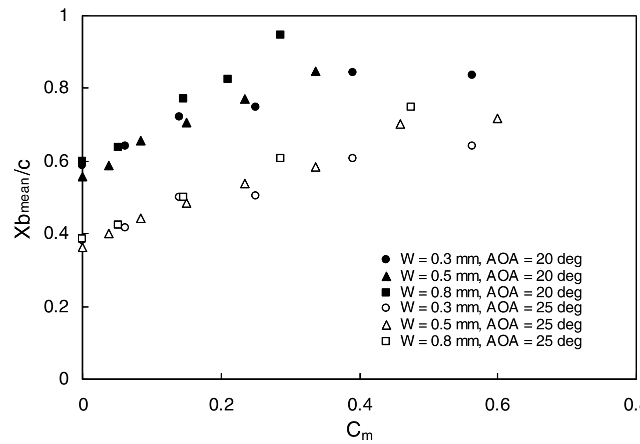


Fig. 15 Effect of slot width on vortex breakdown location vs blowing momentum coefficient at $Re = 4.5 \times 10^4$.

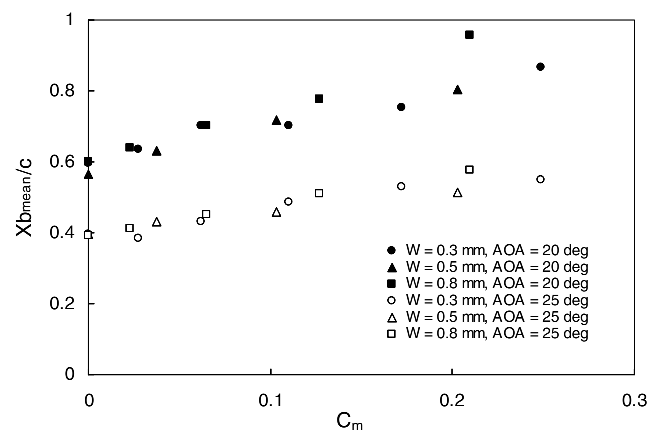


Fig. 16 Effect of slot width on vortex breakdown location vs blowing momentum coefficient at $Re = 6.8 \times 10^4$.

significant affect on the breakdown position. The same behavior is observed at a higher Reynolds number of $Re = 6.8 \times 10^4$ (Fig. 16).

We now compare the forebody slot blowing with other blowing techniques to gain a better understanding of the control mechanism. However, some researchers (see, for example, [23,29]) have used a different form of momentum coefficient that differs by a constant factor of two; for the ease of comparison with our results, their C_m values were adjusted based on the definition in this paper. For trailing-edge blowing, Helin and Watry [21] reported that the vortex breakdown location was delayed up to 18% of the chord for a 60-deg sweep delta wing model at AOA = 20 deg, with the 0-deg vectored trailing-edge jet at the velocity ratio $V_r = 8.0$, correspondingly, $C_m = 1.54$. Shih and Ding [23] showed that by applying a downward 45-deg trailing-edge jet, the vortex breakdown location was delayed 55% chord downstream for their 60-deg sweep delta wing model at AOA = 20 deg with the jet velocity ratio $V_r = 7.3$, correspondingly, $C_m = 5.448$. In our studies, about 35% chord delay was realized for AOA = 20 deg at $C_m = 0.40$, and at $C_m = 0.50$, the vortex breakdown occurs beyond the trailing edge. It is not surprising that the effect of trailing-edge blowing is less effective than our slot blowing, because more energy is needed to relieve the adverse pressure gradient downstream.

For along-core blowing, Kuo and Lin [29] showed that the location of the vortex breakdown increased with increasing the C_m with 60- and 75-deg half sweep delta wing models. For a 60-deg sweep half delta wing model, the vortex breakdown location was delayed by 0.1 c for AOA = 20 deg and by 0.15 c for AOA = 25 deg with $C_m = 0.094$ (see their Fig. 6). For meaningful comparison with our results, it should be noted that because Kuo and Lin used the half model, their results are equivalent to our single-sided blowing. For our asymmetry blowing (one-sided blowing), vortex breakdown can be delayed beyond the trailing edge for AOA = 20 deg and by 0.35 c for AOA = 25 deg with $C_m = 0.074$.

Johari et al. [49] conducted a study using a control technique that they referred to as "recessed angled spanwise blowing" over a 60-deg delta wing, and the maximum delay in the vortex breakdown location of 15% chord was obtained at AOA = 22 deg and $C_m = 0.05$, the effectiveness of which is similar to our results for the case of AOA = 20 deg.

From the preceding comparisons, it appears that the mechanism of forebody slot blowing on delaying the vortex breakdown location is different from that of along-core blowing by increasing the axial velocity or trailing-edge blowing by reducing the downstream pressure gradient. Here, forebody slot blowing controls vortex breakdown by modifying the flowfield near the wing through the rolled-up vortex sheet, like a virtual canard (see Figs. 8, 10, and 12). This is also supported by the results from the effects of slot length and width on vortex breakdown, for which a longer slot appears to be more effective in controlling the vortex breakdown position for the same blowing coefficient, due to the larger interaction area, whereas slot width has little effect on the breakdown position.

IV. Conclusions

Experiments on the use of forebody slot blowing to control vortex breakdown over a generic delta wing-body configuration have been conducted for the Reynolds number ranges from 4.5×10^4 to 8.5×10^4 and for angles of attack of 20, 25, and 28 deg. Time-averaged flow images show that single-sided blowing tends to produce favorable effects on the blowing side and unfavorable effects on the nonblowing side. To compensate for the unfavorable effects, a much higher blowing momentum is needed to delay vortex breakdown on both sides when double-sided blowing is employed. Increasing the blowing momentum leads to a significant delay in the formation of vortex breakdown. For example, at $C_m = 0.2$, about 20% *c* delay was realized for a 20-deg angle of attack, 15% *c* for 25 deg, and 14% *c* for 28 deg. However, when $C_m = 0.4$, the corresponding delays were 35, 20, and 20% *c*, respectively.

It is postulated that when a sheet of fluid is ejected from a forebody slot, it produces a vortex sheet that interacts with the freestream and is rolled up into a trailing vortex further downstream. The rolled-up vortex sheet produces a downwash effect on the blowing side and a sideslip effect on the opposite side. This downwash effect appears to modify the flowfield around the leading edge of the wing, which results in delaying vortex breakdown, like a canard. On the other hand, the sideslip effect promotes vortex breakdown by reducing the effective sweep angle. In addition, a longer slot appears to be more effective in controlling vortex breakdown position for the same blowing coefficient, whereas slot width has little effect on the breakdown position. The present results appear to indicate that forebody slot blowing can be used to delay vortex breakdown on a delta wing more effectively than some existing blowing techniques.

Acknowledgments

The authors gratefully acknowledge the support from the Directorate of Research and Development, Defense Science and Technology Agency, Singapore, under the Flow Control Program POD-0103935.

References

[1] Peckham, D. H., and Atkinson, S. A., "Preliminary Results of Low Speed Wind Tunnel Tests on a Gothic Wing of Aspect Ratio 1.0," British Aeronautical Research Council CP 508, Apr. 1957.

[2] Earnshaw, P. B., and Lawford, J. A., "Low-Speed Wind Tunnel Experiments on a Series of Sharp-Edged Delta Wings," British Aeronautical Research Council, Repts. and Memoranda No. 3424, Mar. 1964.

[3] Lee, M. J., and Ho, C. M., "Vortex Dynamics of Delta Wings," *Frontiers in Experimental Fluid Mechanics*, Lecture Notes in Engineering, Springer, Berlin, Vol. 46, 1989, pp. 365–427.

[4] Hall, M. G., "Vortex Breakdown," *Annual Review of Fluid Mechanics*, Vol. 4, Jan. 1972, pp. 195–218.

[5] Leibovich, S., "The Structure of Vortex Breakdown," *Annual Review of Fluid Mechanics*, Vol. 10, Jan. 1978, pp. 221–246.

[6] Escudier, M. P., "Vortex Breakdown: Observations and Explanations," *Progress in Aerospace Sciences*, Vol. 25, No. 2, 1988, pp. 189–229.

[7] Délery, J. M., "Aspects of Vortex Breakdown," *Progress in Aerospace Sciences*, Vol. 30, No. 1, 1994, pp. 1–59.

[8] Althaus, W., Brucker, C., and Weimer, M., "Breakdown of Slender Vortices," *Fluid Vortices*, edited by S. Green, Kluwer Academic, Norwell, MA, 1995, pp. 373–426.

[9] Lucca-Negro, O., and O'Doherty, T., "Vortex Breakdown: A Review," *Progress in Energy and Combustion Science*, Vol. 27, No. 4, 2001, pp. 431–481.

[10] Mitchell, A. M., and Délery, J., "Research into Vortex Breakdown Control," *Progress in Aerospace Sciences*, Vol. 37, 2001, pp. 385–418.

[11] Rao, D. M., "Leading-Edge Vortex Flap Experiments on a 74° Delta Wing," NASA CR 159161, 1979.

[12] Karagounis, T., Maxworthy, T., and Spedding, G. R., "Generation and Control of Separated Vortices over a Delta Wing by Means of Leading-Edge Flaps," AIAA Paper 89-0997, Mar. 1989.

[13] Gursul, I., Yang, H., and Deng, Q., "Control of Vortex Breakdown with Leading-Edge Devices," AIAA Paper 94-1857, June 1994.

[14] Gursul, I., Srinivas, S., and Batta, G., "Active Control of Vortex Breakdown over a Delta Wing," *AIAA Journal*, Vol. 33, No. 9, 1995, pp. 1743–1745.

[15] Wahls, R. A., Vess, R. J., and Moskovitz, C. A., "Experimental Investigation of Apex Fence Flaps on Delta Wings," *Journal of Aircraft*, Vol. 23, No. 10, 1986, pp. 789–797.

[16] Wood, N. J., Roberts, L., and Celik, Z., "Control of Asymmetric Vertical Flows over Delta Wings at High Angle Of Attack," *Journal of Aircraft*, Vol. 27, No. 5, 1990, pp. 429–435.

[17] Gu, W., Robinson, O., and Rockwell, D., "Control of Vortices on a Delta Wing by Leading-Edge Injection," *AIAA Journal*, Vol. 31, No. 7, 1993, pp. 1137–1186.

[18] Owens, D. B., Perkins, J., "Vortex Suppression on Highly-Swept Wings by Suction Boundary-Layer Control," AIAA Paper 95-0683, Jan. 1995.

[19] McCormick, S., and Gursul, I., "Effective of Shear-Layer Control on Leading-Edge Vortices," *Journal of Aircraft*, Vol. 33, No. 6, 1996, pp. 1087–1093.

[20] Maines, B. H., Moeller, B., and Rediniotis, O. K., "The Effects of Leading-Edge Suction on Delta Wing Vortex Breakdown," AIAA Paper 99-0128, Jan. 1999.

[21] Helin, H., and Watry, C. W., "Effects of Trailing-Edge Jet Entrainment on Delta Wing Vortices," *AIAA Journal*, Vol. 32, No. 4, 1994, pp. 802–804.

[22] Nawrocki, D., "Differential and Vectored Trailing-Edge Jet Control of Delta Wing Vortices," AIAA Paper 95-0008, Jan. 1995.

[23] Shih, C., and Ding, Z., "Trailing-Edge Jet Control of Leading Edge Vortices of a Delta Wing," *AIAA Journal*, Vol. 34, No. 7, 1996, pp. 1447–1456.

[24] Vorobieff, P. V., and Rockwell, D. O., "Vortex Breakdown on Pitching Delta Wing: Control by Intermittent Trailing-Edge," *AIAA Journal*, Vol. 36, No. 4, 1998, pp. 585–589.

[25] Mitchell, A. M., Molton, P., Barberis, D., and Délery, J., "Control of Leading-Edge Vortex Breakdown by Trailing-Edge Injection," *Journal of Aircraft*, Vol. 39, No. 2, 2002, pp. 221–226.

[26] Wang, J. J., Li, Q. S., and Liu, J. Y., "Effects of a Vectored Trailing Edge Jet on Delta Wing Vortex Breakdown," *Experiments in Fluids*, Vol. 34, No. 5, Nov. 2003, pp. 651–654.

[27] Parmenter, K., and Rockwell, D., "Transient Response of Leading-Edge Vortices to Localized Suction," *AIAA Journal*, Vol. 28, No. 6, 1990, pp. 1131–1132.

[28] Miller, S., and Gile, B., "The Effects of Blowing on Delta Wing Vortices During Dynamic Pitching at High Angles of Attack," AIAA Paper 92-0407, Jan. 1992.

[29] Kuo, C. H., and Lin, D. C., "Non-Uniform Recovery of Vortex Breakdown over Delta Wing in Response to Blowing Along Vortex Core," *Experiments in Fluids*, Vol. 22, No. 1, Nov. 1996, pp. 33–44.

[30] Kuo, C. H., Lu, N. Y., and Lin, D. C., "Evolution of Vertical Structure over Delta Wing with Transient Along-Core Blowing," *AIAA Journal*, Vol. 35, No. 4, 1997, pp. 617–624.

[31] Kuo, C. H., and Lu, N. Y., "Unsteady Vortex Structure over Delta-Wing Subject to Transient Along-Core Blowing, " *AIAA Journal*, Vol. 36, No. 9, 1998, pp. 1658–1664.

[32] Mitchell, A. M., Barberis, D., Molton, P., and Délery, J., "Oscillation of Vortex Breakdown Location and Blowing Control of the Time Averaged Location," *AIAA Journal*, Vol. 38, No. 5, 2000, pp. 793–803.

[33] Dixon, C. J., "Lift Augmentation by Lateral Blowing over a Lifting Surface," AIAA Paper 69-193, Feb. 1969.

[34] Bradley, R. G., and Wray, W. O., "A Conceptual Study of Leading-Edge Vortex Enhancement by Blowing," *Journal of Aircraft*, Vol. 11, No. 1, 1974, pp. 33–38.

[35] Behrbohm, H., "Basic Low-Speed Aerodynamics of the Short-Coupled Canard Configuration of Small Aspect Ratio," Svenska Aeroplan Aktiebolaget TN-60, Sweden, July 1965.

[36] Lamar, J. E., "Analysis and Design of Strake-Wing Configurations," *Journal of Aircraft*, Vol. 17, No. 1, 1980, pp. 20–27.

[37] Er-El, J., and Seginer, A., "Vortex Trajectories and Breakdown on Wing-Canard Configurations," *Journal of Aircraft*, Vol. 22, No. 8, 1985, pp. 641–648.

[38] Er-El, J., "Effect of Wing/Canard Interference on the Loading of a Delta Wing," *Journal of Aircraft*, Vol. 25, No. 1, 1988, pp. 18–24.

[39] Tu, E. L., "Navier-Stokes Simulation of a Close-Coupled Canard-Wing-Body Configuration," *Journal of Aircraft*, Vol. 29, No. 5, 1992, pp. 830–838.

[40] Tu, E. L., "Effect of Canard Deflection on Close-Coupled Canard-Wing-Body Aerodynamics," *Journal of Aircraft*, Vol. 31, No. 1, 1994, pp. 138–145.

[41] Tu, E. L., "Vortex-Wing Interaction of a Close-Coupled Canard Configuration," *Journal of Aircraft*, Vol. 31, No. 2, 1994, pp. 314–321.

[42] Hummel, D., and Oelker, H. C., "Low-Speed Characteristics for the Wing-Canard Configuration of the International Vortex Flow Experiment," *Journal of Aircraft*, Vol. 31, No. 4, 1994, pp. 868–878.

[43] Howard, R. M., and O'Leary, J. F., "Flowfield Study of a Close-Coupled Canard Configuration of the International Vortex Flow Experiment," *Journal of Aircraft*, Vol. 31, No. 4, 1994, pp. 908–914.

[44] Seginer, A., Salomon, M., "Augmentation of Fighter Aircraft Performance by Spanwise Blowing over the Wing Leading Edge,"

NASA TM-84330, Mar. 1983.
[45] Rao, D. M., "Recent Studies of Slot-Blowing Techniques for Vortex Breakdown Control on Slender Configurations," *Fluid Dynamics of High Angle of Attack*, Springer–Verlag, Berlin, 1992, pp. 237–253.
[46] Lowson, M. V., "Some Experiments with Vortex Breakdown," *Journal of the Royal Aeronautical Society*, Vol. 68, No. 641, 1964, pp. 343–346.
[47] Gursul, I., "Unsteady Flow Phenomena over Delta Wings at High Angle of Attack," *AIAA Journal*, Vol. 32, No. 2, Feb. 1994, pp. 225–231.
[48] Menke, M., Yang, H., and Gursul, I., "Experiments on the Unsteady Nature of Vortex Breakdown over Delta Wings," *Experiments in Fluids*, Vol. 27, No. 3, Aug. 1999, pp. 262–272.
[49] Johari, H., Olinger, D. J., and Fitzpatrick, K. C., "Delta Wing Vortex Control via Recessed Angled Spanwise Blowing," *Journal of Aircraft*, Vol. 32, No. 4, 1995, pp. 804–810.

G. Candler
Associate Editor