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Errata

Trailing-Edge Jet Control of Leading-Edge Vortices of a Delta Wing

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PAGES 1451 and 1452 were mistakenly printed with coding errors. Both pages are shown herewith in their correct form.

showing no sign of tapering off, as the jet velocity is increased. At the maximum jet velocity, the breakdown location is delayed 58% chord downstream.

The effect of trailing-edge jets has also been studied by Helin and Watry[17] who used a 0-deg jet nozzle configuration for control. Their results are also included in Fig. 7 for comparison. Their data show a consistently higher (more favorable) X_b/C value for the vortex breakdown location as compared with our 0-deg jet case. Although both groups use a 60-deg delta wing, our model is much thicker than theirs since an internal chamber is included inside the wing body for a smooth expansion of the trailing-edge jet. As mentioned before, it is speculated that the discrepancy in vortex breakdown location is mainly due to the difference in the thickness of the models.

The trailing-edge control jet creates a local streamwise favorable pressure gradient region near the trailing edge that tends to relieve the overall adverse pressure gradient imposed by the external flow. It is reasonable to argue that the favorable pressure gradient created by the trailing-edge jet depends on its strength or, in other words, the jet velocity. When the jet velocity is low, its favorable influence is only limited to a small local region, and its influence can not be felt upstream where the severe adverse pressure gradient dominates. Therefore, there is no delay of the vortex breakdown below a certain threshold limit.

Another interesting thing to note is the steadiness of the vortex axis angle that is defined as the angle between the centerline of the delta wing and the vortex axis (which can be clearly identified from the dye streak). The vortex axis always assumes a 19 ± 1-deg angle and is essentially independent of the AOA of the delta wing, even under dynamic pitching conditions. Also, when the trailing-edge control jet is turned on, no significant change of the vortex axis angle can be observed except very close to the trailing edge where the dye streak is turned inside towards the centerline. This suggests that the flow separation at the leading edge of the delta wing is a robust process and is not easily subject to other influences. Although the trailing-edge jet has a significant effect on the leading-edge vortex flow, the vortex axis stays unchanged. The fact that the vortex core always stays on the same straight line is also important for measurement of the flow along the vortex core using PIV. It is therefore possible to project the illuminating laser sheet precisely along the entire vortex core.

Dynamic Pitching Cases

When the delta wing undergoes a transient pitching motion, a delay of the onset of vortex breakdown to a higher AOA as compared with static case is consistently observed. This delay is closely linked to the dynamic effect of the pitching motion. An experimental investigation of ramp-type pitch-up motion with a nondimensionalized pitch rate ranging from 0.043 to 0.26 is carried out to study the dynamic effect. The delta wing is pitched from an AOA of 10 to 45 deg. The wing accelerates at a constant rate to achieve its desired constant rotational speed in less than 6% of C/U_∞ for all pitch rates tested. Similar to the static cases, the vortex breakdown location is measured from the apex of the delta wing. A video camera is used to record the flow visualization results. Its temporal resolution of 30 frames/s is sufficient to resolve the propagation of the instantaneous vortex breakdown location even for the highest pitch rate case, $\alpha^+ = 0.26$.

No Control

Figure 8 shows the progression of the vortex breakdown point with respect to the nondimensional time variation for pitching without jet control cases. When the delta wing first starts the ramp-type

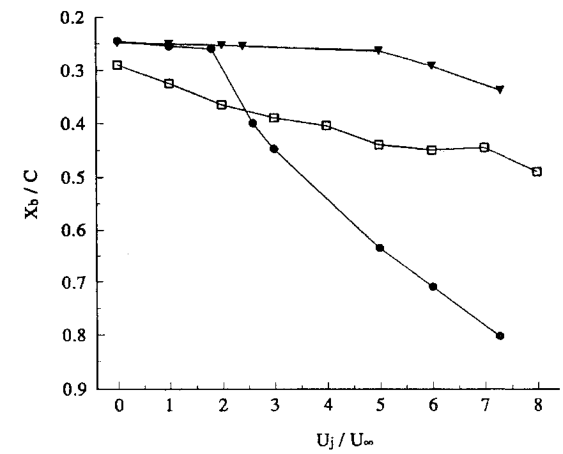

Fig. 7 Effect of trailing-edge jet velocity on vortex breakdown, AOA = 20 deg: ▾, 0-deg jet; •, 45-deg downward jet; and □, data from Helin et al.[17]

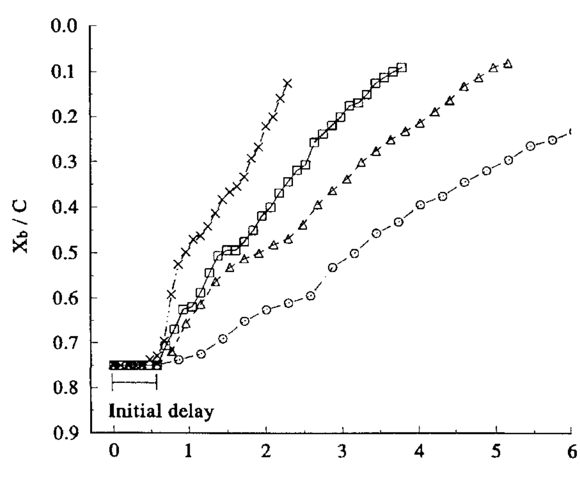

Fig. 8 Breakdown location vs time, no control, different pitch rates: ○, pitch rate 0.043; △, pitch rate 0.086; □, pitch rate 0.130; and ×, pitch rate 0.260.

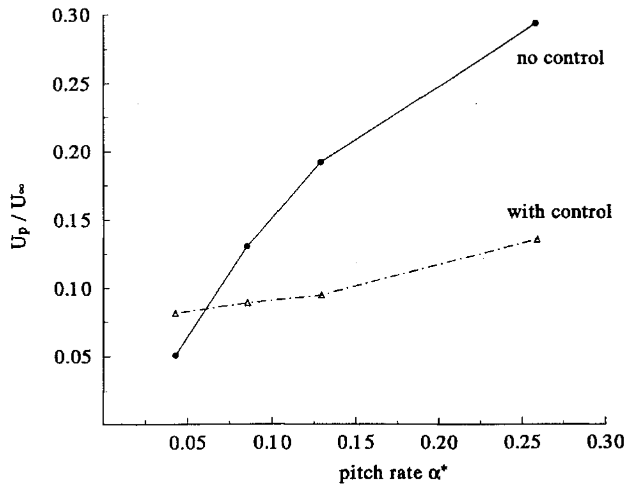

Fig. 9 Propagation velocity of the vortex breakdown location.

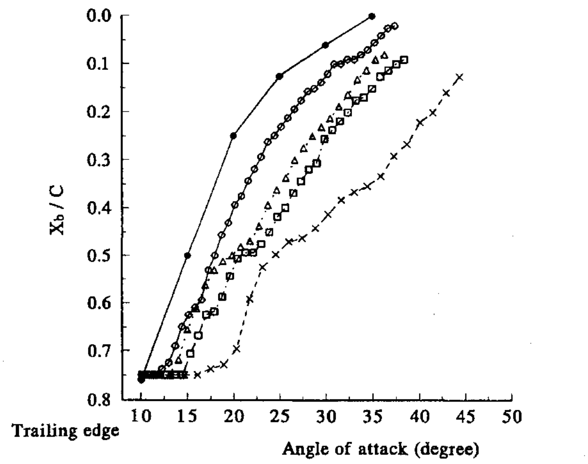

Fig. 10 Vortex breakdown location vs AOA, no control, different pitch rates: •, static AOA; ○, pitch rate = 0.043; △, pitch rate = 0.086; □, pitch rate = 0.13; and ×, pitch rate = 0.26.

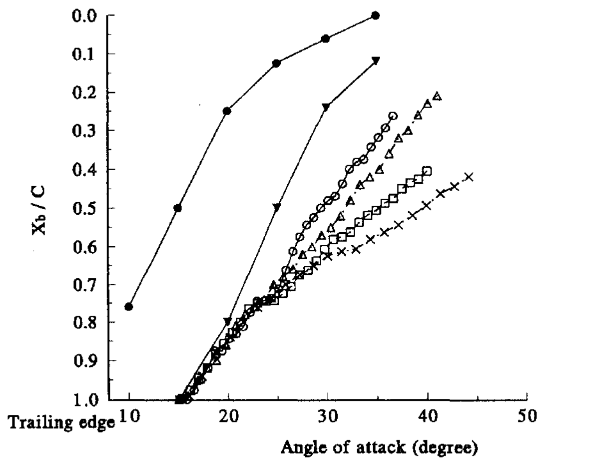

Fig. 11 Vortex breakdown location vs AOA, with 45-deg downward jet control, different pitch rates: •, static AOA; ▾, static AOA with control; ○, pitch rate = 0.043; △, pitch rate = 0.086; □, pitch rate = 0.130; and ×, pitch rate = 0.260.

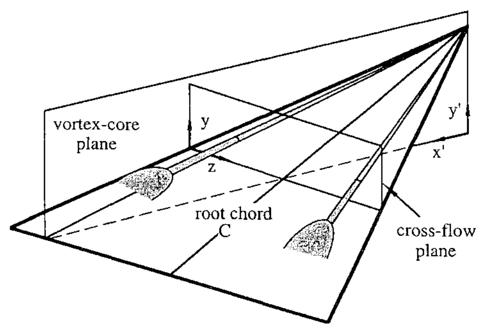

Fig. 12 Coordinate systems for PIV measurement.

pitching motion, the vortex burst location appears to be unaffected by the movement for a period of time. Miau et al.[24] suggested that this delay is caused because the primary vortex can not respond instantaneously to the sudden change of the AOA and that its growth is lagging behind the initial ramp-up motion. As a result, this underdeveloped structure probably experiences a less severe adverse axial pressure gradient and can stay unburst longer as compared with a static case at the same AOA. If one accepts this argument, it is expected that the initial delay time should be correlated to the time required for the primary vortex to adjust itself to the newly changed flow condition. In other words, the delay should be closely linked to the time required for the newly generated vorticity from the leading edge to be entrained into the primary vortex. This delay should be relatively insensitive to the pitching rates (also shown by Ref. 24). It appears that, within the range tested in the present investigation, the initial delay is also independent of the pitch rates. However, the estimated initial delay of 0.58 is lower than the value of 1.0 obtained by other studies.[24] The difference is probably caused by the use of nonstandard (20% C thick) delta wing configuration in the present experiment. After the initial delay, the vortex breakdown location moves quickly upstream with a higher propagation speed, especially for the higher pitch rate cases. It is speculated that, because of the initial delay, the fully established leading-edge vortex experiences a more severe adverse pressure gradient since the wing has already pitched to a higher AOA. This adverse condition accelerates the upstream progression of the breakdown. As the breakdown moves further upstream, this progression appears to experience another slowdown, which has been attributed[24] to the interaction between the secondary vortex and the primary vortex. After the second delay, the vortex breakdown point resumes its upstream movement with a relatively constant speed for each pitch rate. The propagation speed can be estimated by least-square fitting the data points (excluding data points that correspond to the initial delay) from this figure, and the results are presented in Fig. 9 along with the controlled cases. It can be clearly seen that the higher the pitch rate, the faster the vortex breakdown propagates upstream. It approaches 29% of the freestream velocity for the highest pitch rate for the uncontrolled case. Other factors, such as the pitch rate induced camber effect,[25,26] may also contribute to the delay of vortex breakdown. However, a comprehensive discussion of these effects is beyond the scope of the current works.

Note that the behavior of the dye streaks under unsteady conditions is more unpredictable compared with that of the static case. Therefore, it is more difficult to identify precisely the vortex breakdown location. This problem is especially serious during the initial pitching-up period. An uncertainty of $\pm 3\%$ chord for the estimation of the vortex breakdown location is expected.

The vortex breakdown progression vs AOA is presented in Fig. 10. For the lowest pitch rate of $\alpha^+ = 0.043$, the trend of vortex breakdown position after the initial delay appears to match closely that of the static case. As the pitch rate is increased, the unsteady effect becomes increasingly dominant. For all AOA, there is always a higher percentage of the vortex stays unburst for a higher pitching rate case. For example, at the highest pitch rate, $\alpha^+ = 0.26$, the vortex can stay unburst for about 35% chord length at 35-deg AOA. At this angle, the static case has already experienced total vortex breakdown.

With Jet Control

The use of trailing-edge jet control has been shown to be effective in delaying the leading-edge vortex breakdown process under static conditions. It is expected that the control system should produce a similar favorable effect under dynamic pitching-up motion. To examine this, a 45-deg downward vectoring nozzle configuration with a maximum jet velocity of $7.3U_\infty$ is used. The data are presented in Fig. 11. For comparison, data sets from static cases both with and without jet control are also included. The jet control is turned on before the initiation of the pitching-up motion to ensure a steady jet output. For all cases with jet control (both static and dynamic conditions), no vortex breakdown can be observed on the delta wing surface at AOA less than 15 deg. Beyond that angle, the breakdown point starts to move quickly upstream. However, it is interesting to note that, during the initial propagation period ($X_b/C > 80\%$), all data for different pitch rates are essentially collapsed into one curve that also coincides closely with the data from the static with control case. This suggests that the breakdown process is dominated by the presence of jet control, for either static or dynamic conditions, as long as the vortex breakdown location remains close to the trailing edge. The dynamic effect becomes increasingly evident as all unsteady curves, including the lowest pitch rate case, start to deviate from the static one beyond 20-deg AOA. However, this dominant jet effect does not diminish until the wing pitches to AOA higher than 25 deg. Only after that, the unsteady effect for different pitch rates begins to show. For example, 45% of the vortex remains unburst at 45-deg AOA for the highest pitch rate ($\alpha^+ = 0.26$), which is a dramatic improvement over the static uncontrolled case.

The use of jet control not only can delay the initiation of the vortex breakdown to a higher AOA, it also slows down the propagation of the breakdown process (see Fig. 9). Significant reductions of the propagation speed of the breakdown location are achieved for all but the lowest pitch rate ($\alpha^+ = 0.043$) tested. For example, at the highest pitch rate, the propagation speed reduces from 29 to 14% freestream velocity when the control jet is used.

PIV Measurements

To provide a more quantitative understanding of the leading-edge vortex flow, PIV measurements are taken along selected planes. The first set includes several crossflow planes that are normal to the direction of the freestream, the y and z coordinates are directions normal to the freestream and parallel to the wing surface, respectively, with their origins fixed at the left side leading edge of the wing (Fig. 12). The second set of PIV measurement are taken along the vortex core plane that aligns with one of the vortex cores. The x' and y' are aligned in the horizontal and vertical direction, respectively, along the vortex core plane (Fig. 12). For all of the PIV cases presented

AIAA regrets these errors.

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