AIAA JOURNAL
Vol. 30, No. 6, June 1992

Effect of Tunnel Walls on Vortex Breakdown Location over Delta Wings

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Vortex breakdown has been the subject of many investigations during the past few decades. Many of the investigations were performed by visualizing the vortical flowfield above delta wings in water or wind tunnels. In spite of the extensive use of this technique, little attention has been paid to the possible influence of the test section walls on the measured location of the vortex breakdown. The present work suggests a possible model by which the walls may affect the vortex breakdown location. The suggested model is associated with the upwash induced on the wing surface due to the presence of the walls. This upwash was found to be relatively small near the wing's apex and larger on the trailing edge, thus creating an effectively cambered wing. The effective camber tends to shift the vortex breakdown location downstream as compared to a flat wing with the same projected geometry. The influence of the walls was tested in a series of experiments in a water tunnel using delta wings with different sizes, relative to the test section dimensions. The anticipated trend was observed in the experimental results.

Nomenclature

C_r = wing root chord length
H = test section height
U = undisturbed velocity
S = wing span
W = test section width
X_{bd} = vortex breakdown location along the wing root chord
α = angle of attack
Λ_{LE} = leading-edge sweep angle

I. Introduction

THE vortex breakdown phenomenon has been the subject of many investigations in the past decades, both analytical and experimental. Despite the great interest, the exact mechanism leading to vortex breakdown is still a matter of some debate.[1] In spite of the diversity, there appears to be agreement among the researchers as to the main physical parameters influencing the phenomenon. For example, adverse pressure gradients tend to promote the occurrence of breakdown.[2-4] A review of the research done in this field is given in a number of publications, such as Refs. 1, 5, and 6.

Some of the vortex breakdown investigations were performed by visualizing the vortical flowfield above delta wings, mapping the vortex breakdown location as a function of the angle of attack, and the wing leading-edge sweep angle (i.e., Refs. 7 and 8). A popular tool in these experiments is a water tunnel in which the leading-edge vortex cores are visualized by dye injected into the flow from the apex. In spite of the fact that some of the wings used in the water-tunnel visualizations were large, as compared to the test section, the possible influence of the tunnel walls on the vortex breakdown location was omitted from many of these investigations. Werle[7] comments on a certain correction applied to the angle of attack due to the presence of the test section walls, but no details are given with regard to this correction.

Since the vortex breakdown phenomenon is affected by local flowfield properties, such as pressure gradient, the wall influence can be somewhat more complex than just a simple bias in a global property of the flowfield, and there exists a need for estimating the local influence of the test section walls. The present work suggests a possible explanation for the influence of the test section walls on the vortex breakdown location.

II. Approximate Modeling of the Influence of the Walls

The modeling of the test section wall interference was done by replacing the wall with eight images of the vortices inside the test section, accounting for the first of an infinite number of layers needed for an exact representation of the four straight walls.[9] Two pairs of vortices have been taken into account inside the test section: 1) the separated leading-edge vortices, and 2) an additional pair of vortices representing the wing's bound vorticity. The vortices' paths were taken along straight lines from the wing's apex to above (or on for the bound vortices) the trailing edge. The lateral and vertical position of the separated vortices above the trailing edge have been estimated based on experimental results presented by Mendenhall and Nielsen[10] and Marsden et al.[11] The lateral position of the bound vortices has been evaluated using computational results obtained by TILLM,[12] which contracts the vorticity shed from the leading-edge of a delta wing in accordance with Sack's theorem. The vortices' strength has been estimated following Mendenhall and Nielsen,[10] who have combined Sack vortex impulse theorem[13] with Polhamus' leading-edge suction analogy.[14]

The results obtained by the simplified method described earlier are compared in Fig. 1 to results obtained by Frink[15] using the free vortex sheet (FVS) method to simulate the wing surface and the test section walls. The discrepancies between the more accurate FVS method and the present calculations are not dramatic and do not affect the essence of the estimated walls effects.

Figure 2 presents the upwash distribution along the wing as computed for the relative wing sizes used in the experiments of Werle[7] and Thompson.[8] As can be seen, the induced upwash is relatively small near the wing's apex and grows larger toward the trailing edge—a fact that creates an effectively cambered wing under the influence of the test section walls.

Only a few publications exist with experimental data on the influence of wing camber on the vortex breakdown location (i.e., Refs. 16 and 17). From these publications, it seems that cambering a delta wing positively (the local incidence at the trailing edge is larger than at the apex) causes a delay in the

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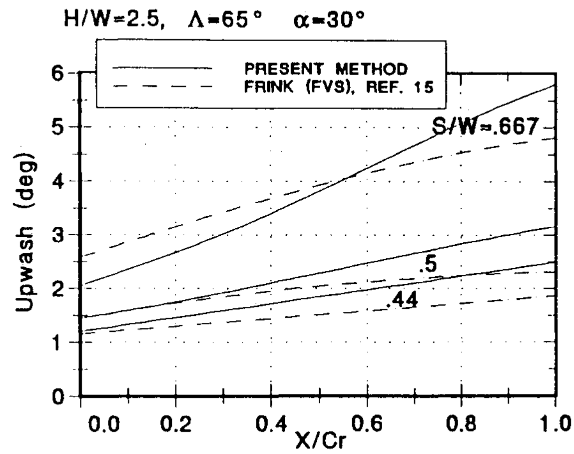

Fig. 1 Approximated evaluation results as compared to the FVS method.

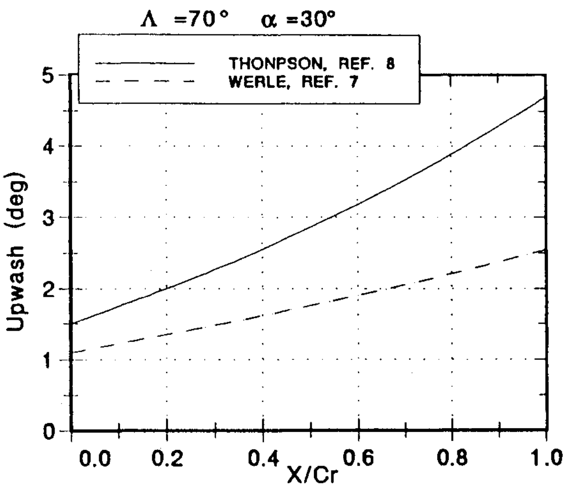

Fig. 2 Approximated evaluation results for the test geometries used in Refs. 7 and 8.

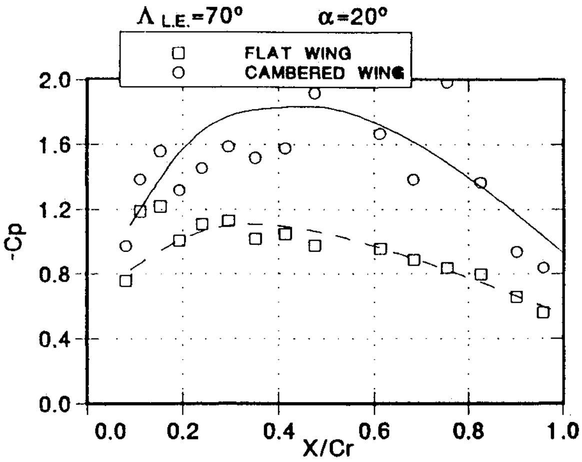

Fig. 3 Pressure coefficient along the vortex core above flat and cambered delta wings.

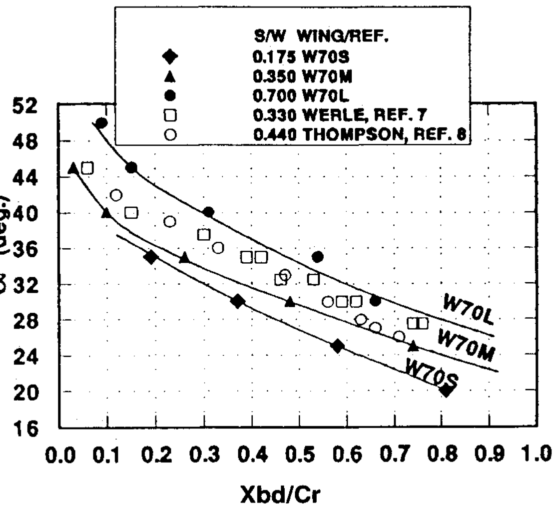

Fig. 4 Measured vortex breakdown location for various wing sizes, 70-deg leading-edge sweep.

vortex breakdown when compared to a flat wing with the same leading-edge sweep. These results were, however, obtained using wings with different amounts and shapes of camber applied to the wing, which makes the earlier conclusion only qualitative.

A suggested mechanism by which the wing camber affects the vortex breakdown location can be exploited by evaluating the separated flowfield above a cambered wing using an appropriate computer code. The code chosen for this evaluation is VLMSP2.[18] This code utilizes a nonlinear vortex lattice method and is capable of tracing the trajectory of the vortex filaments separated from swept-back leading edges.

The pressure coefficient along the vortex core, as computed by VLMSP2, is presented in Fig. 3 for flat and cambered delta wings having the same planar geometry. The shape of the camber applied to the wing is identical to the effective camber acquired during the test by Thompson[8] and presented in Fig. 2. As can be seen in Fig. 3, the pressure on the flat wing reaches its lowest value at about 0.3 of the chord length before starting to rise toward the trailing edge. The minimum pressure location above the cambered wing is delayed to farther downstream (to about 0.5 of the chord length) due to the continuously increasing local incidence along the wing chord. Since vortex breakdown is promoted by the adverse pressure gradient, the vortices above the flat wing are expected to burst closer to the apex than those of the cambered wing at the same angle of attack.

The aforementioned conclusion, with regard to tunnel test of vortex breakdown above swept-back wings, is opposite to the intuitive result that wall effects tend to increase the effective angle of attack. Such an increase in angle of attack will result in correcting the breakdown location backward, whereas the appropriate correction of the breakdown locations, when the effective camber is taken into account, is forward.

III. Experimental Investigation in the Wall Effect

The effect of the size of a delta wing relative to that of the test section on the vortex breakdown location has been investigated experimentally using flow visualization in the Rafael Water Tunnel (RWT) in Israel. The water tunnel has a test section of 45 × 45 cm and its maximum velocity for continuous operation is 50 cm/s. The models tested consist of two sets of delta wings having 60- and 70-deg leading-edge sweep. The wings in each set differ from one another in their linear dimensions. The spans of the wings are 79 (W60S, W70S), 158 (W60M, W70M), and 316 mm (W60L, W70L). Special attention has been paid to the exact similarity of the wings in each set, including the local geometry of the leading edges. The flow visualization was carried out by emitting dye from the two sides in the immediate vicinity of the wing apex. The dye was delivered to the apex in two tubes (0.8-mm external diameter) glued to the lower surface from the supporting rod along the lower surface midchord. The flow velocity during

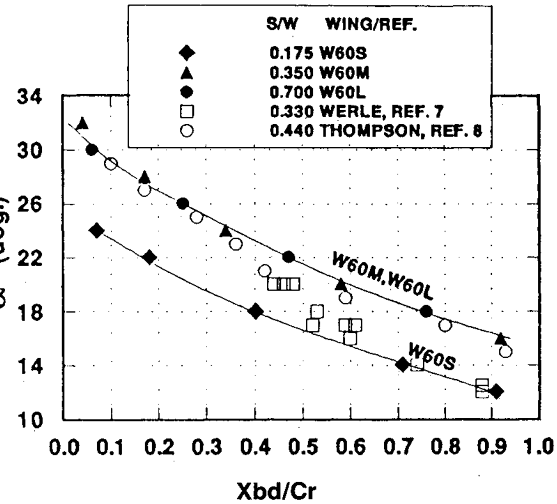

Fig. 5 Measured vortex breakdown location for various wing sizes, 70-deg leading-edge sweep.

the experiments was 11 cm/s. The smaller wing models (W60S, W70S) were tested, in addition, at velocities ranging from 4 to 21 cm/s. The velocity variation in this range did not have a significant influence on the vortex breakdown location as a function of the angle of attack.

The measured vortex breakdown position, as a function of angle of attack, is presented in Figs. 4 and 5 for the two values of leading-edge sweep tested. As can be seen in Fig. 4, the results for the 70-deg sweepback wing follow the trend anticipated in Sec. II. The breakdown location, at some constant angle of attack, moves continuously backward as the wing grows larger. The results of Refs. 7 and 8 shown in Fig. 4 fit, at least qualitatively, the trend of the influence of the test section walls on the breakdown location. The breakdown location over these wings is, consequently, in the vicinity of the breakdown over the W70M wing (which has about the same relative size), whereas the breakdown moves forward for the smaller wing (W70S) and backward for the larger one (W70L).

The breakdown location for the 60-deg sweepback wings (Fig. 5) does not follow the predicted trend of Sec. II above as well as for the higher sweepback. The breakdown location is shifted backward as the wing size is increased (from W60S to W60M), but further increase of the wing size (from W60M to W60L) does not have any further influence on the breakdown location. This trend suggests that the effective camber acquired by the wing due to wall effect is not the only agent of the walls influence. When comparing the experimental results to the predicted, one has also to realize that the method of images used here is valid only for small aspect ratio wings. The deviation from this small aspect ratio assumption might be too large for a 60-deg swept wing, and so the discrepancy between the predicted trend and the experimental results might be expected. The experimental results of Thompson[8] coincide with the curve obtained with the relatively large wings (W60M and W60L). This fact is consistent with the wing span to test section width ratios of the wings. Werle's results[7] which were measured for a relative wing sizes slightly smaller than W60M, coincide with the W60S results at smaller angles of attack and then, as the angle of attack is increased, the results gradually shift toward the results obtained with the W60M and W60L wings.

IV. Conclusions

A mechanism through which the presence of the test section walls may influence the vortex breakdown location measured over a wing in a tunnel has been suggested. The walls create an effectively cambered wing, a fact that tends to move the breakdown, at a specific angle of attack, backward. This trend was verified experimentally for wings with relatively low aspect ratio only.

Acknowledgments

The author would like to express his gratitude to H. Portnoi for his support and encouragement throughout this work and to D. Almosnino for making possible the use of VLMSP2 in the current research. Special gratitude is extended to Y. Mattityahu for his technical assistance in the experimental work.

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