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# Aspects of Ground Facility Interference on Leading-Edge Vortex Breakdown

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**Because of the current high interest in low observables planforms, characterized by swept leading-edge and trailing-edge panels, it is appropriate to consider the implications for ground facility testing of models that, because of the existing coupling between opposing leading-edge vortices, must be of the full-span variety. To shed light on this topic, the existing extensive experimental database for delta wings is reviewed to determine what parts wall interference, support interference, and Reynolds number played in the observed ground facility interference.**

## Nomenclature

$b$ = wingspan
$c$ = wing root chord
$N$ = normal force, coefficient $C_N = N/(\rho_\infty U_\infty^2/2)S$
$p$ = static pressure, coefficient $C_p = (p - p_\infty)/(\rho_\infty U_\infty^2/2)$
$Re$ = Reynolds number based on $c$ and freestream conditions
$S$ = reference area (projected wing area)
$t$ = time
$U$ = horizontal velocity
$w$ = width of test section
$x$ = axial body-fixed coordinate
$y$ = spanwise body-fixed coordinate (Fig. 9)
$z$ = vertical body-fixed coordinate (Fig. 9)
$\alpha$ = angle of attack
$\alpha_c$ = pitch-rate-induced camber (Fig. 6)
$\Gamma$ = circulation (Fig. 5)
$\Lambda$ = leading-edge sweep angle
$\xi$ = dimensionless $x$ coordinate, $x/c$
$\rho$ = air density
$\sigma$ = inclination of the roll axis
$\phi$ = roll angle

*Subscripts*

$A$ = apex
$B$ = vortex breakdown
$c$ = camber
eff = effective
$\infty$ = freestream conditions

## Introduction

WITH the current interest in low-observables (LO) configurations, which are characterized by swept leading-edge and trailing-edge panels, there is a pressing need to resolve long-standing questions regarding the effects of ground facility interference on vortex breakdown. Ground facility interference comprises two equally important components, that is, support interference and wall interference. An analysis of recently published experimental results reveals that this has often been overlooked. For instance, the difference between test results for differently sized models of otherwise equivalent delta-wing geometries is often ascribed totally to one of the two components, for example, wall interference, as in the cases to be discussed here.

A recent review and further analysis of factors influencing the vortex breakdown measured on delta wings[1] reveals inconsistencies, which could have been introduced by the presence of both components of ground facility interference. The results of these experiments and associated analysis[1] appear at first glance to contradict the conclusions drawn from an earlier analysis.[2] This illustrates the complexity of the facility interference problem. In the present paper an effort is made to update the earlier analysis[2] by addressing the inconsistencies described in Ref. 1.

## Discussion

Figure 1 shows that increasing the size of the 70-deg delta wing model caused the vortex breakdown to occur closer to the apex.[1] This data trend, obtained in water-tunnel tests at $Re = 3.5 \times 10^4$, is opposite to that obtained in earlier water-tunnel tests[3] (Fig. 2). The general trend in the latter results can be explained by the longitudinal wing camber generated by the wall-induced upwash along the leading edge of the delta wing.[2,3] The results in Fig. 1 were also explained in Ref. 1 by the wall-induced upwash effect, represented, however, by the resulting increase of the effective angle of attack at the wing center of pressure. When correcting the measurements (Fig. 1) for this alpha effect, the results regrouped as shown in Fig. 3. Although the spread between the curves is decreased in Fig. 3 compared to Fig. 1, the conclusion drawn[1] that "the curves collapse rather well" is not well founded. For some reason, the data set for the midsized model ($c = 7$ in.), which fell midway between the original, uncorrected curves in Fig. 1, falls outside of the collapsed curves for the smaller ($c = 4.93$ in.) and larger size ($c = 14$ in.) models in Fig. 3.

It is well established that vortex breakdown moves toward the apex with increasing angle of attack,[4] as is illustrated by Figs. 1 and 2. Consequently, the wall-induced increase of the effective angle of attack should have promoted breakdown, as stated in Ref. 1. However, experimental results of the effect of camber on the vortex breakdown of an 80-deg delta wing[5] (Fig. 4) indicate that the wall-induced camber effect[2,3] should dominate over the effect of the increase of the mean angle of attack. In the case of the positive camber (Fig. 4a), the angle of attack at the wing center of pressure is large compared to that for the negative camber (Fig. 4b). Still, vortex breakdown occurs downstream of the trailing edge in the former case (Fig. 4a), in sharp contrast to the occurrence of breakdown close to the apex for the case of negative camber, in spite of the lower angle of attack

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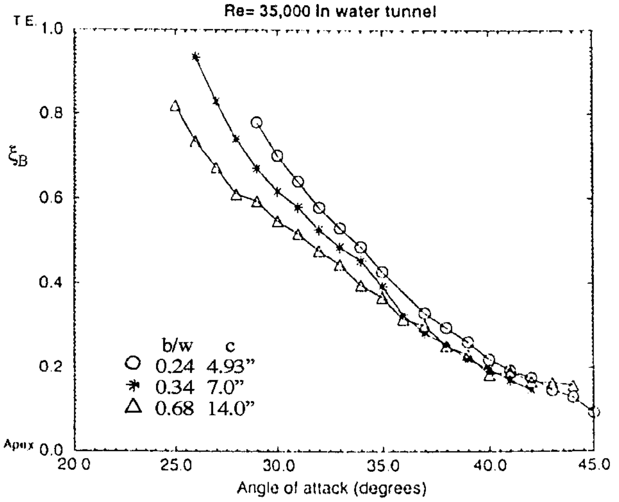



**Fig. 1 Effect of model size on vortex breakdown of 70-deg delta wing.[1]**

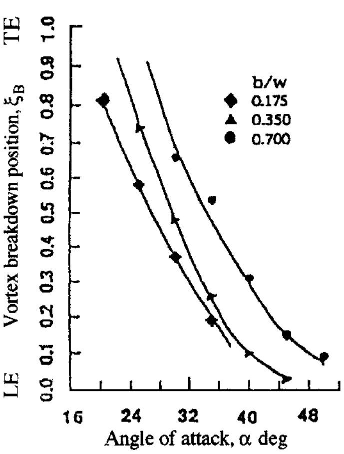



**Fig. 2 Wind-tunnel wall interference effects on the vortex breakdown of 70-deg delta wing.[3]**

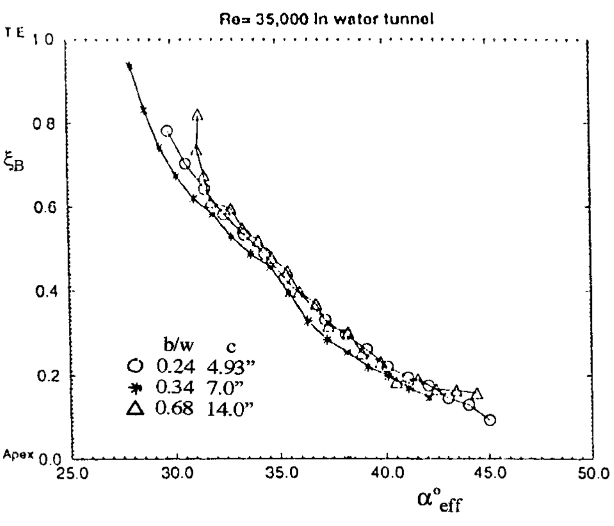


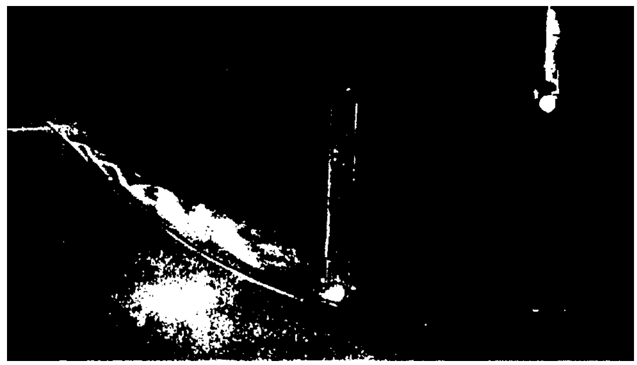

**Fig. 3 Effect of model size on vortex breakdown of 70-deg delta wing as function of effective angle of attack.[1]**

over the central wing area (Fig. 4b). Thus, one can definitely not neglect the wall-induced camber effect, as is done in Ref. 1. However, from Fig. 4 it would appear to be justified to neglect the wall-induced change of the effective, mean angle of attack, the only effect considered in Ref. 1. The theoretical basis for this reasoning is as follows.

## Effects of Induced Camber

The delta wing analysis in Ref. 6, which utilizes Polhamus's leading-edge-suction analogy,[7] shows that the vortex lift is solely

a)



b)

**Fig. 4 Effect of a) positive and b) negative camber on the vortex breakdown of 80-deg delta wing.[5]**

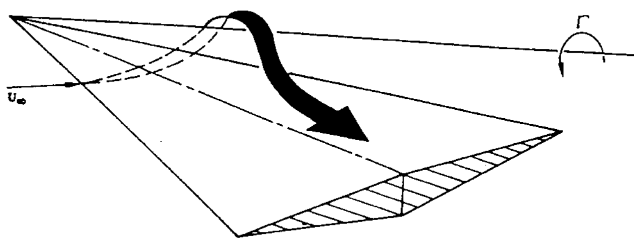



**Fig. 5 Entrainment effect of the leading-edge vortex.[6]**

determined by the local crossflow conditions at the leading edge. In contrast, the loads on the inboard portion of the wing are not only dependent on the local, effective angle of attack but are also influenced by the flow conditions at the leading edge through the flow entrainment action of the leading-edge vortices (Fig. 5). Additionally, it was shown in Ref. 8 that the effect of sideslip on the vortex lift was determined satisfactorily by only considering the local flow conditions at the leading edge. This was also found to be the case for the determination of the effect of roll angle and roll rate on the vortex-induced lift and associated rolling moment.[9] It is, therefore, no surprise to find that the local flow conditions at the leading edge are completely dominant over the flow conditions existing over the inner wing when determining the location of vortex breakdown[5] (Fig. 4). The same is also true when considering the relative effects of pitch-rate-induced camber $\alpha_c$(Fig. 6)[10] and the effective, mean angle of attack. The large overshoot of static $C_{N\max}$, observed during the upstroke for a pitching delta wing[11] (Fig. 7), is mainly a result of the pitch-rate-induced positive camber $\alpha_c$ (Fig. 6). The negative camber generated during the downstroke promotes breakdown, resulting in the measured large undershoot of static $C_{N\max}$, all in agreement with the observed effects of camber on static vortex breakdown[5] (Fig. 4).

In the case of the roll-rate-induced camber effect[12] (Fig. 8), there is no correspondence to the rate-induced effective angle of attack generated over the center wing area of a pitching delta wing. Only the roll-rate-induced changes of the crossflow angle of attack at

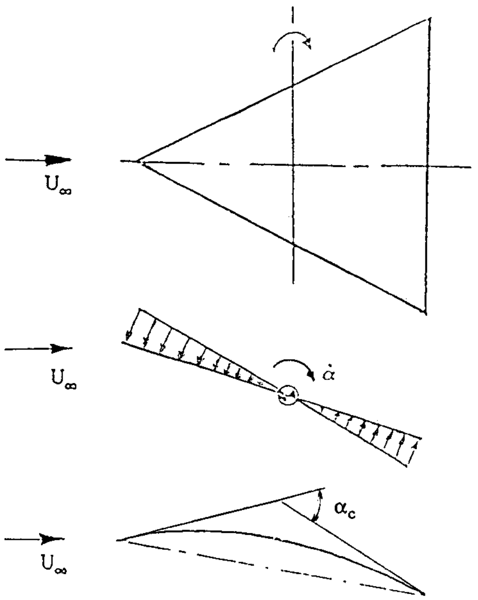



**Fig. 6 Pitch-rate-induced camber effect on a slender delta wing.**[10]

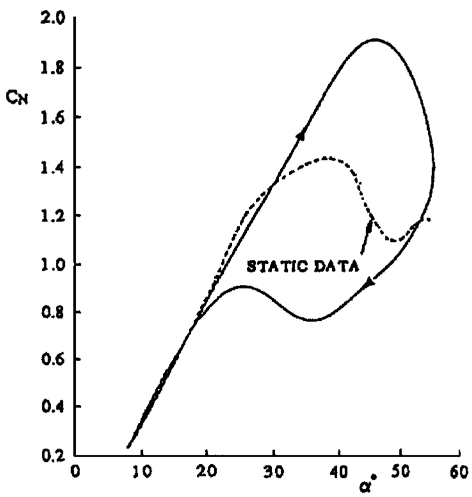



**Fig. 7 Dynamic $C_N(\alpha)$ characteristics of a pitching, sharp-edged 70-deg delta wing.**[11]

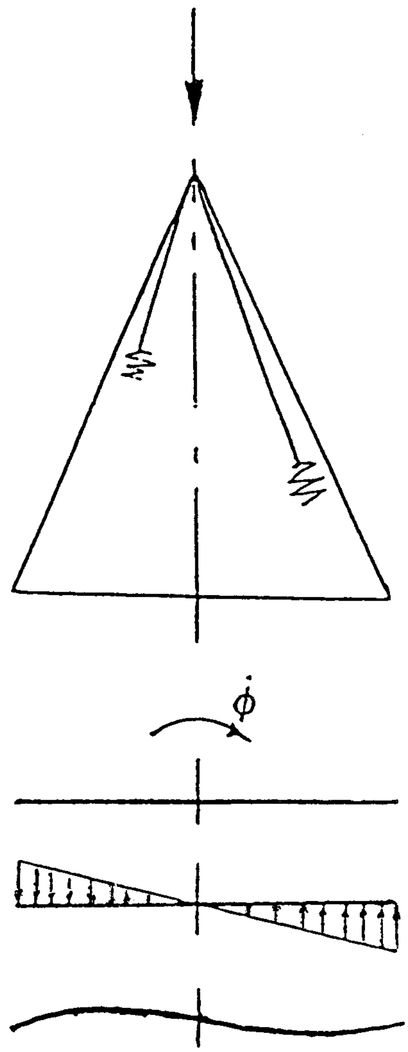



**Fig. 8 Roll-rate-induced camber effect.**[12]

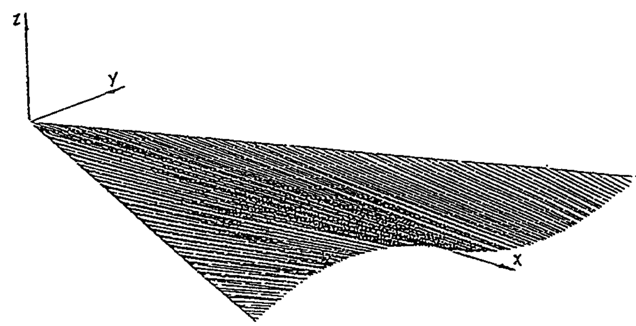



**Fig. 9 Thin sheet-metal model deformed to represent the dynamically equivalent steady roll-rate-induced camber effect on 65-deg delta wing.**[13]

the leading edge can have an effect on the vortex breakdown. Tests with a thin sheet-metal model, deformed to produce the conical camber generated at zero roll angle in high-rate/large-amplitude roll oscillations at $\sigma = 30$ deg of a 65-deg delta wing[13] (Fig. 9) gave the expected changes of the location of vortex breakdown[14] (Fig. 10).

Thus, the data trend in Fig. 1 cannot be explained through representing the wall interference by the upwash induced at the wing center of pressure, as suggested in Ref. 1. It must be a result of other important components of ground facility interference,[2] that is, other manifestations of wall interference,[15] or support interference,[16,17] which in high-alpha tests often is of more concern than the wall interference.

## Coupled Support and Wall Interference

Unfortunately, there is no useful information in Ref. 1 about the support structure used. However, it is reasonable to assume that the same support structure was used for the three models. It has been demonstrated by Hummel[18] that an obstacle placed one chord length downstream of the trailing edge of the delta wing caused vortex breakdown to move from a position downstream of the trailing edge to roughly midchord (Fig. 11). It has also been shown that the sting–strut support structure used in high-alpha tests has a similar effect, greatly promoting vortex breakdown on a delta-wing model.[15,16] If the sting–strut support structure was one chord length downstream of the trailing edge of the large model ($c = 14$ in. in Fig. 1), one would expect, based on Fig. 11, that vortex breakdown would have been promoted to occur farther forward of the trailing edge than in the absence of the support structure. In the case of the smaller models ($c = 7$ and 4.93 in. in Fig. 1) the sting–strut juncture would have been, respectively, 2 and 2.85 chord lengths downstream of the trailing edge, causing progressively less obstruction with associated decreased promotion of vortex breakdown, all in agreement with the test results in Fig. 1. Note that support interference can be minimized using newly developed techniques.[19,20]

In a more recent investigation,[21] the effect of model size on the location of vortex breakdown on a 70-deg delta wing was measured

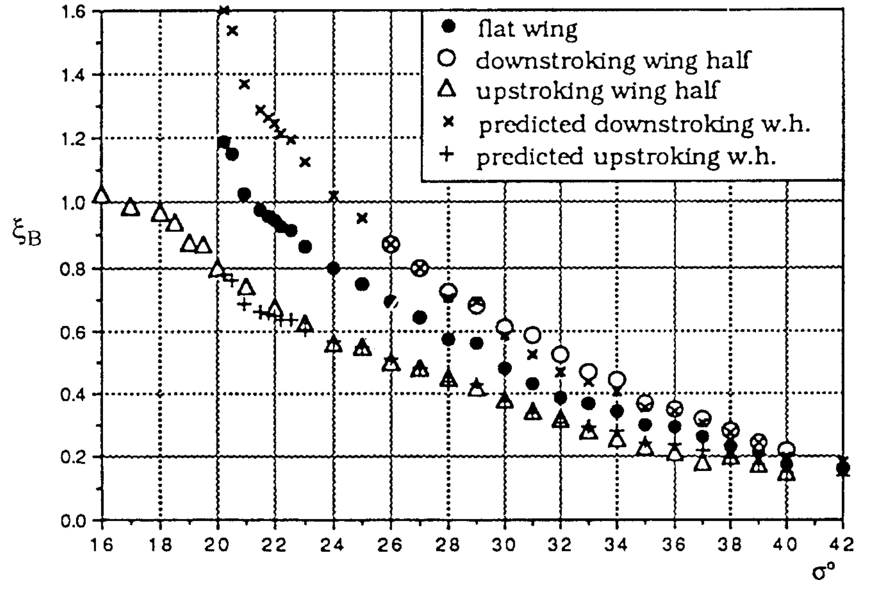



**Fig. 10 Measured effect of the dynamically equivalent steady maximum roll-rate-induced camber effect on the vortex breakdown at $\sigma$ = 30 deg and $\phi$ = 0 on a 65-deg delta-wing–body configuration.[14]**

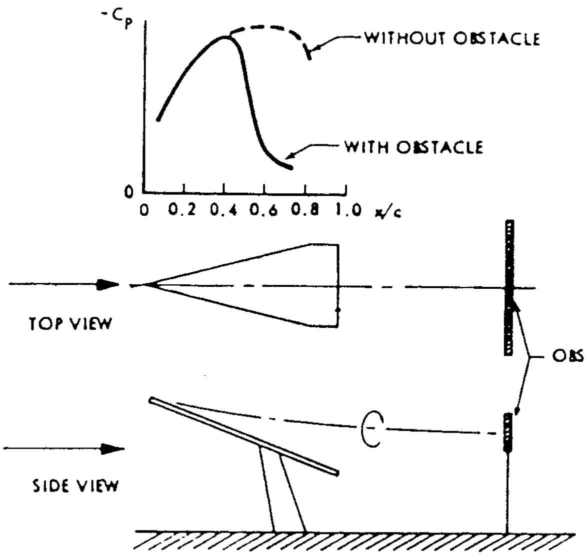



**Fig. 11 Promotion of vortex breakdown on 75-deg delta wing caused by a downstream obstacle.[18]**

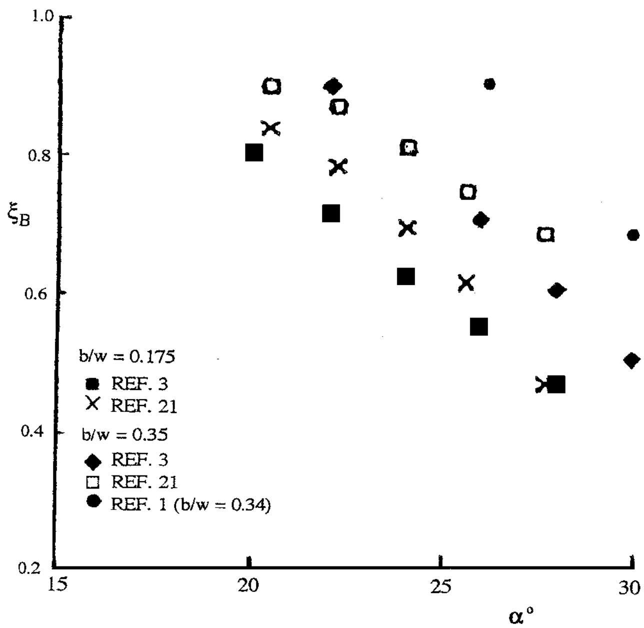



**Fig. 12 Comparison of vortex breakdown on 70-deg delta wing measured in different test facilities.**

in wind-tunnel tests at $Re = 5 \times 10^4$, producing laminar flow conditions similar to those that existed in the water-tunnel tests[1,3] (Fig. 12). The emphasis in Ref. 21 was on the effect of wall interference and, as in Ref. 1, no information was given about the support structure. The comparison in Fig. 12 with Weinberg's water-tunnel results[3] shows relatively good agreement, especially for $b/w = 0.35$. When the results for $b/w = 0.34$ from Ref. 1 are considered, the situation becomes more complicated. Assuming that the support structure used in Ref. 21 was similar to that used in Ref. 1 and that the support interference in Ref. 1 was small for $b/w = 0.34$ (and $b/w = 0.24$), the results in Fig. 12 would indicate that for $b/w = 0.35$ support interference caused vortex breakdown in Refs. 3 and 21 to occur 20% of chord upstream of that observed in Ref. 1. Decreasing the model size to $b/w = 0.175$ should have increased the chordwise distance from the model to the support structure sufficiently to cause the support interference to possibly become of negligible magnitude. Thus, for both $b/w = 0.175$ and 0.35 the differences between Refs. 3 and 21 probably fall within the data accuracy in the two tunnel facilities. For the larger model size in Fig. 12 ($b/w = 0.35$), both appear to have had more severe support interference than in the University of Notre Dame facility[1] (Fig. 1), a natural result of dimensioning the support structure for the test of the large model ($b/w = 0.68$). This would have resulted in the support structure being twice as far downstream of the model (measured in chord lengths) for $b/w = 0.34$ than for $b/w = 0.68$. The associated diminished support interference at $b/w = 0.34$ would be smaller than in a test planned for $b/w \leq 0.35$, as in Refs. 3 and 21.

## Nonuniform Flow due to Test Installation

When a strut support structure is used, the class of interference discussed with reference to Fig. 11 is generally the most severe.[15] However, when a large model is tested, the situation becomes more complex. Vortex breakdown is promoted upstream of the strut flow stagnation region, but delayed in the outer region of the test section where the strut produces a favorable pressure gradient. Comparing Figs. 1 and 2, one notes that the curves for $b/w = 0.175$ and 0.35 in Fig. 2 follow a trend similar to that in Fig. 1, but that the vortex breakdown is delayed for $b/w = 0.7$, particularly at higher angles of attack. This indicates that additional parameters are at play. It is likely that the longitudinal static pressure gradient near the tunnel wall could have had a significant effect on vortex breakdown for the large model ($b/w = 0.700$ in Fig. 2). At low alpha, the adverse longitudinal pressure gradient due to the presence of the support will promote vortex breakdown. However, with increasing alpha, the increasing wake blockage of the delta wing produces a dynamic pressure increment with associated favorable static pressure gradient in the outer region.[15] Unsteady tests of aircraft models have shown that this effect increases rapidly for relative model sizes $b/w > 0.5$ (Ref. 22). In the case of $b/w = 0.700$ in Fig. 2, this effect appears to have delayed vortex breakdown substantially, the delay increasing rapidly with increasing angle of attack, in agreement with expectations.[15] In contrast, the data at $b/w = 0.68$ in the water tunnel (Fig. 1) display a breakdown delay that decreases with increasing incidence. Whereas the difference in Reynolds number, support geometries, and the presence/absence of a mounting body are likely to have played an important role, there are other factors that also need to be considered. Note that the nature of wall interference in a horizontal-circuit water tunnel is different from that in the wind tunnel owing to the presence of a free surface. For large blockage ratios, the test section flow is distorted by turbulence due to surface gravitational action and the dynamic pressure increment is opposite to that for solid walls. The difference in test Reynolds number for the two models could also have played a role.

## Interdependence of Facility-Interference and Reynolds Number Effects

The test engineer's dilemma when trying to investigate the effect of Reynolds number on delta-wing vortex breakdown is well illustrated by the experimental results in Fig. 1. The experimental results in Fig. 2 can be used to illustrate the problem encountered when investigating the effect of leading-edge sweep, while keeping the delta-wing chord constant to keep the Reynolds number constant. In that case, the ratio $b/w$ will vary with the sweep angle $\Lambda$ as follows:

$$b/w = (2c/w)\cot\Lambda \tag{1}$$

Equation (1) shows that if $b/w = 0.175$ for $\Lambda = 80$ deg decreasing the sweep to $\Lambda = 70$ and 60 deg would result in $b/w = 0.36$ and $b/w = 0.57$, respectively. The results in Fig. 2 indicate that these $b/w$ values would prevent the test from showing the true effect of the leading-edge sweep.

Although it is undeniably true that both support interference and wind-tunnel wall interference can in many cases severely distort the experimental results, it should be emphasized that a test engineer knowledgeable about these difficulties can select model size and test parameters that will bring these ground facility interference effects down to tolerable magnitudes. Note that the interference effect on vortex breakdown becomes of even greater concern for a delta wing describing pitching or rolling motions.[2]

## Conclusions

Analysis of published experimental results for a 70-deg delta wing leads to the conclusion that, in subscale tests of wings with highly swept leading edges, the concerns of Reynolds number scaling, wind-tunnel wall interference, and model support interference place conflicting requirements on the test parameters that need to be considered in the early planning stages to assure the quality of the test results. Accounting for these effects is shown to reduce discrepancies significantly between wind-tunnel and water-tunnel measurements.

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