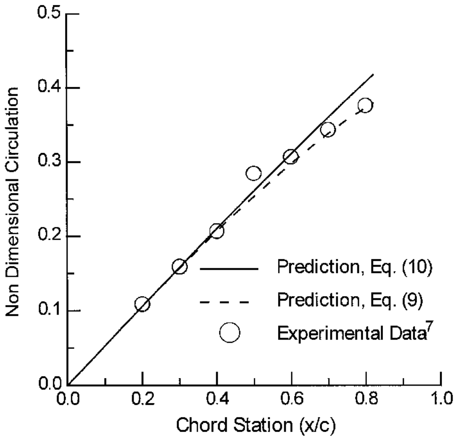


**Fig. 2 Comparison of theory and experiment for chordwise variation of circulation, $\Lambda = 75$ deg, $\alpha = 20$ deg.**

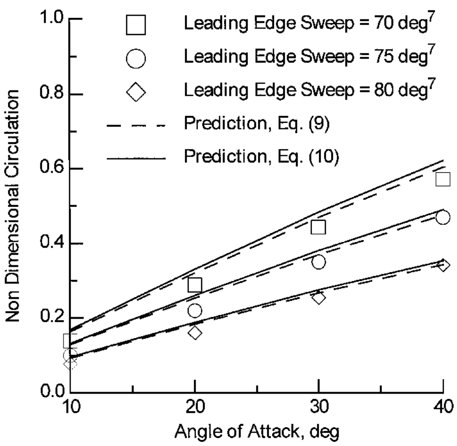


**Fig. 3 Comparison of theory and experiment for variation of circulation with sweep and incidence, $x/c = 0.5$.**

The similarity of the form of Eq. (13) to that for the AR of a delta (AR = 4 tan $\varepsilon$) is interesting. Figure 1 also shows comparisons of $k_p$ calculated using Eq. (13) and data from Ref. 1; it may be seen that Eq. (13) demonstrates excellent accuracy for AR < 2, as would be expected. Also included in the figure is the result for the lift–curve slope of slender deltas as per slender wing theory, i.e., $k_p = (\pi/2)$AR.

To estimate the constant $K$ for delta wings, comparisons of Eqs. (9) and (10) with experimental results of Visser and Nelson[7] are shown in Figs. 2 and 3. The circulation values presented are nondimensionalized by the freestream and wing root chord. Setting $K = 0.5$ yields the correlations shown. Figure 2 shows that the present method displays very good correlation with the experimentally determined chordwise vortex circulation distribution. Notice that over the forward part of the wing, Eqs. (9) and (10) are in good agreement. As the trailing edge is approached, Eq. (10) tends to predict higher circulation values, as would be expected noting its formulation. Although not directly modeling the physics, Eqs. (9) and (10) do predict the correct trends,[6] i.e., over the forward part of the wing the leading-edge circulation and vortex circulation are similar; however, as the trailing edge is approached the vortex circulation increases beyond that of the leading-edge circulation. Figure 3 shows that the method closely predicts the trends of sweep and $\alpha$ on $\Gamma/U_\infty c$. The experimental circulation shown is the maximum measured at the $x/c = 0.5$ location. The predicted results in Fig. 3 were calculated by evaluating Eq. (9) at $b/4$ (i.e., $x/c = 0.5$), and integrating Eq. (10) spanwise from the wing root to $b/4$.

## Concluding Remarks

A method is presented that predicts the leading-edge vorticity and vortex circulation for delta wings. The method relates the strength of the vorticity shed to the rate of change of leading-edge thrust. Circulation was calculated by both integrating the vorticity distribution as well as integrating the sectional circulation distribution. The study suggests that the leading-edge vortex strength is proportional to the normal component of the freestream and the wing lift–curve slope, with sweep effects effectively being included in the lift–curve slope. The dependence of vortex strength on the potential constant and angle of attack also allows determination of two simple expressions for the attached flow lift–curve slope of delta wings.


## Acknowledgment

The author would like to thank Murray Tobak for his helpful comments and suggestions.


## References


[1]Polhamus, E. C., "A Concept of the Vortex Lift of Sharp-Edge Delta Wings Based on a Leading-Edge Suction Analogy," NASA TN D-3767, Oct. 1966.

[2]Purvis, J. W., "Analytical Prediction of Vortex Lift," *Journal of Aircraft*, Vol. 18, No. 4, 1981, pp. 225–230.

[3]Katz, J., and Plotkin, A., *Low Speed Aerodynamics, from Wing Theory to Panel Methods*, 1st ed., McGraw–Hill, New York, 1991, pp. 558–562.

[4]Kumar, A., "Accurate Development of Leading Edge Vortex Using an Embedded Conical Grid," *AIAA Journal*, Vol. 34, No. 10, 1996, pp. 2038–2046.

[5]Hemsch, M. J., and Luckring, J. M., "Connection Between Leading Edge Sweep, Vortex Lift, and Vortex Strength for Delta Wings," *Journal of Aircraft*, Vol. 27, No. 5, 1990, pp. 473–475.

[6]Longo, J. M. A., "Compressible Inviscid Vortex Flow of a Sharp Edge Delta Wing," *AIAA Journal*, Vol. 33, No. 4, 1995, pp. 680–687.

[7]Visser, K. D., and Nelson, R. C., "Measurements of Circulation and Vorticity in the Leading-Edge Vortex of a Delta Wing," *AIAA Journal*, Vol. 31, No. 1, 1993, pp. 104–111.


# Impact of Initial Conditions on Vortex Breakdown on Pitching Delta Wings


Lars E. Ericsson*
*Mt. View, California 94040*


## Introduction

WHEN comparing the experimental results[1] at $\bar{\omega} = 0.10$ for a 52-deg delta wing (Fig. 1) with those for $\bar{\omega} = 0.107$ (Fig. 2) for a 65-deg delta wing,[2] the following question arises. Why can the upstroke characteristics in Fig. 1 hardly get downstream of the static characteristics, especially considering that even during the initial portion of the downstroke the vortex breakdown in Fig. 2 prefers to stay on the downstream side of the static characteristics? These vortex breakdown characteristics[2] were analyzed in Ref. 3 by first considering the characteristics for purely rampwise changes of the angle of


Presented as Paper 96-3405 at the AIAA Atmospheric Flight Mechanics Conference, San Diego, CA, July 29–31, 1996; received Nov. 3, 1996; revision received Feb. 18, 1997; accepted for publication March 5, 1997.




*Engineering Consultant. Fellow AIAA.

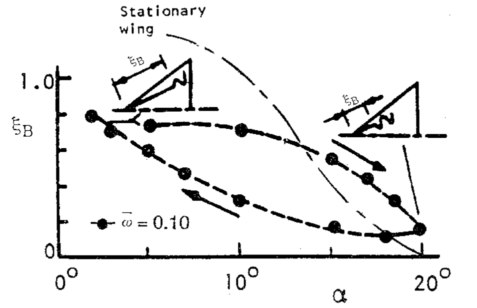


**Fig. 1 Vortex breakdown characteristics for $\bar{\omega}$ = 0.10 compared to static $\bar{\omega}$ = 0 results.**[1]

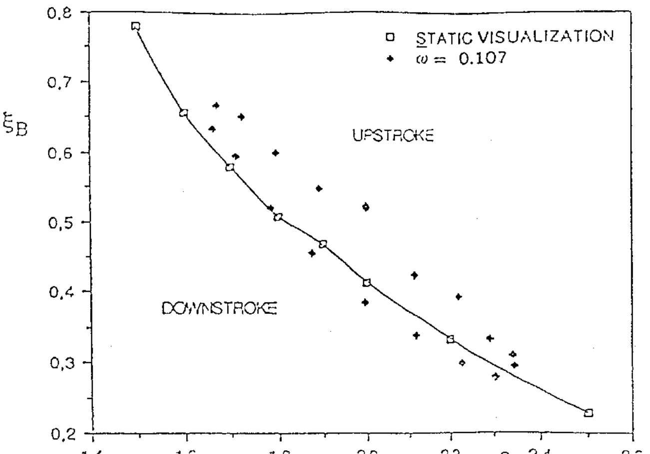


**Fig. 2 Vortex breakdown location on a sharp-edged 65-deg delta describing oscillations in pitch.**[2]

attack.[4] It was shown that the delay of breakdown for a pitch-up motion and the promotion for a pitch-down motion were caused by the pitch-rate-induced camber effect, in agreement with static experimental results.[5]

### Oscillatory Motions

Figure 3 shows a comparison of the static breakdown characteristics and the pitch-rate-induced camber effects, $\Delta\alpha_c = \dot{\alpha}c/U_\infty$, for the 10-deg oscillation around $\alpha_0$ = 10 deg of the 52-deg delta wing[1] and the 3.5-deg oscillation around $\alpha_0$ = 20 deg of the 65-deg delta wing.[2] It can be seen that in the case of the 65-deg delta wing static vortex breakdown is occurring at approximately 40% chord at $\alpha = \alpha_0$ = 20 deg, where the pitch-rate-induced camber is of maximum magnitude. In contrast, static vortex breakdown occurs aft of the trailing edge for the 52-deg delta wing at $\alpha = \alpha_0$ = 10 deg. As the movement of vortex breakdown onto the delta wing is associated with static hysteresis,[6] the pitch-rate-induced camber during the upstroke is likely to be able to keep the breakdown behind the trailing edge of the 52-deg delta wing until the angle of attack approaches $\alpha$ = 20 deg. As a consequence, the first action of the pitch-rate-induced camber on the location (forward of the trailing edge) of the breakdown on the 52-deg delta wing will be to promote it, moving vortex breakdown forward during the downstroke (Fig. 1). In contrast, for the 65-deg delta wing the vortex breakdown never moves past the trailing edge (Fig. 3), avoiding the complex, nonlinear aerodynamics associated with this critical state.[7,8] Consequently, the initial pitch-rate-induced camber effect is to delay breakdown during the upstroke for the 3.5-deg oscillations around $\alpha$ = 20 deg (Fig. 2). How this difference in initial conditions could cause the observed large changes of the oscillation loops in Figs. 1 and 2 is the question that needs to be answered.

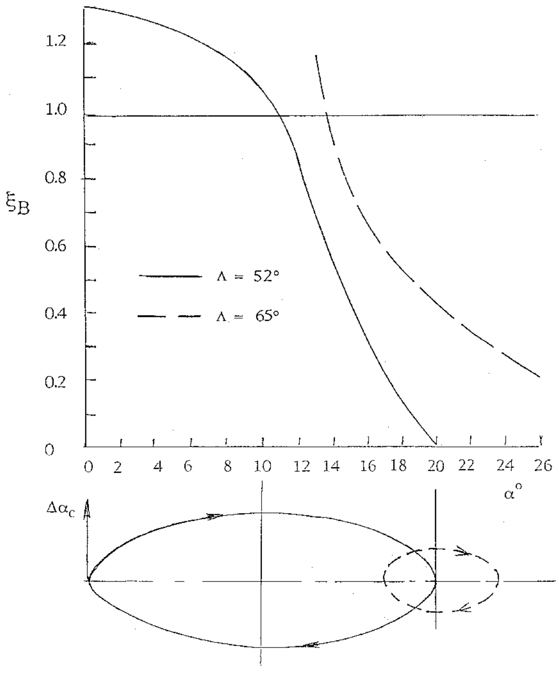


**Fig. 3 Static vortex breakdown $\xi_B$ and pitch-rate-induced camber $\Delta\alpha_c$ for 52- and 65-deg delta wings.**

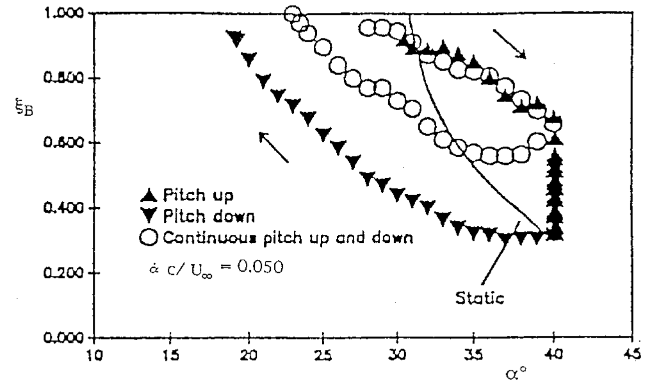


**Fig. 4 Different effects on the vortex breakdown of a 70-deg delta wing of single up or down pitch ramps and continuous up and down ramps.**[9]

### Ramp Motions

The experimental results[9] in Fig. 4 for a 70-deg delta wing illustrate the fact demonstrated by Reynolds and Abtahi[10]: that it takes a very long time for the vortex to reach the static equilibrium conditions in the presence of breakdown. Based upon the results in Fig. 4 one can construct two scenarios. When the initial action was a positive $\alpha$ ramp, starting at $\alpha \approx$ 27 deg, the characteristics shown in Fig. 4 resulted. Figure 5 illustrates the probable characteristics that would have resulted if the initial action had been a negative $\alpha$ ramp, from $\alpha$ = 40 deg. In the case of an oscillatory rather than rampwise change of the angle of attack, the characteristics in Fig. 5 could be expected to take a shape similar to that shown in Fig. 1.

The experimental results for a rampwise increase of the angle of attack, $\alpha(\tau)$, obtained by Reynolds and Abtahi[10] (Fig. 6), demonstrate that it takes considerable time for the pitch-rate-induced effects on vortex breakdown to dissipate. The runs of different time duration, $4.58 \geq T \geq 1.23$ s for $\dot{\alpha}c/U_\infty$ = 0.12, correspond to runs at $0.068 \leq U_\infty \leq 0.125$ m/s, i.e., $1.9 \times 10^4 \leq Re \leq 6.5 \times 10^4$, contributing to the large data scatter in Fig. 6. It should be noted that much of the difference between dynamic and static $\xi_B = f(\alpha)$ can be accounted for by the dynamically equivalent steady (DES) effects of the effec-

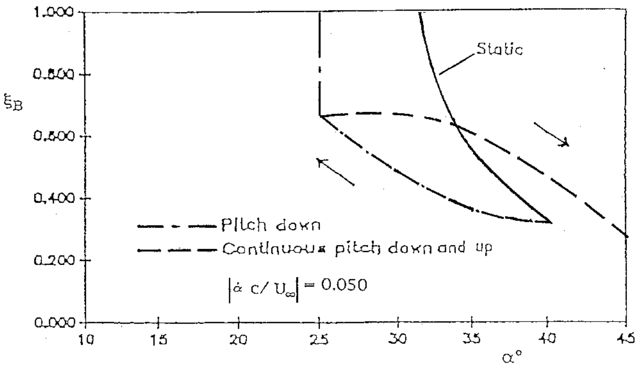


**Fig. 5 Conceptual effects of initial pitch-down motion on vortex breakdown characteristics for a 70-deg delta wing.**

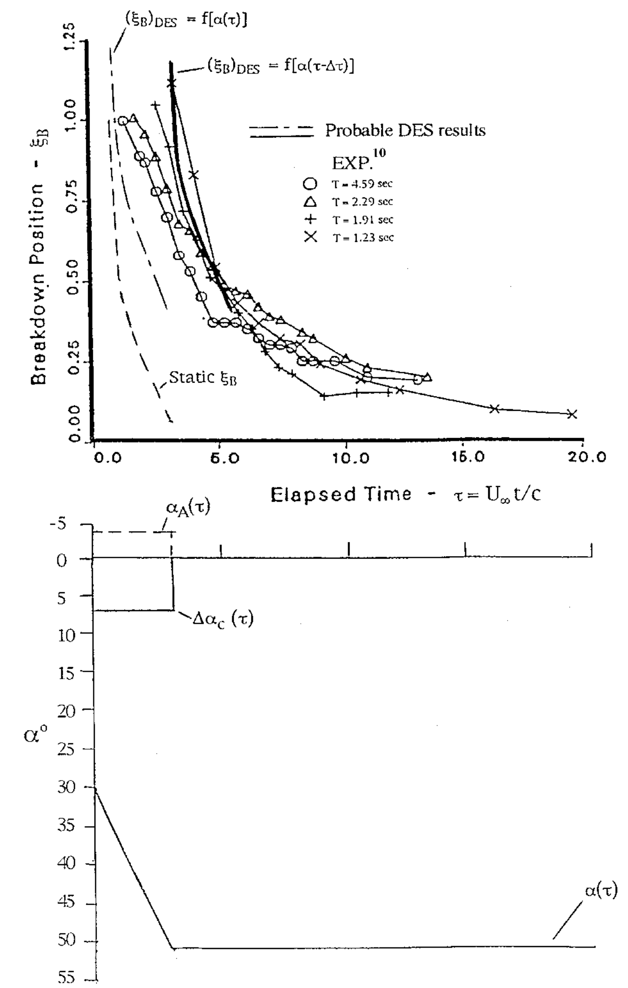


**Fig. 6 Conceptual time–history effects on vortex breakdown for rampwise increase of the angle of attack of a 75-deg delta wing.**

tive angle of attack $\alpha_A(\tau)$ at the apex and the pitch-rate-induced camber effect $\Delta\alpha_c = \alpha_{TE} - \alpha_A = \dot{\alpha}c/U_\infty$ (Fig. 6); $\alpha_A(\tau) = -3.5$ deg delays the vortex development to start at $\alpha(\tau) - \alpha_A(\tau) = \alpha(\tau) + 3.5$ deg, represented by the static $\xi_B = f(\tau)$ in Fig. 6. The pitch-rate-induced camber effect $\Delta\alpha_c(\tau) = 6.9$ deg delays vortex breakdown to occur at $(\xi_B)_{DES} = f[\alpha(\tau)]$, as sketched in Fig. 6. Accounting for time–history effects by means of a constant time lag $\Delta\tau$ yields the sketched $(\xi_B)_{DES} = f[\alpha(\tau - \Delta\tau)]$. The static $\xi_B = f(\alpha)$ has been defined experimentally.[11] The remaining difference to the experimental results is the truly transient effect of losing the rate-induced vortex structure developed during the $\alpha$ ramp.

In contrast to the case of the $\alpha$ ramp, for an oscillatory change of the angle of attack the vortex structure developed during the upstroke, stays on for a substantial part of the downstroke, and vice versa. This causes the transient, longer-time-scale characteristics, associated with the relaxation to static characteristics, to have insignificant effects on the oscillatory $\xi_B = f(\tau)$. The resulting decreased complexity provides an opportunity for the development of prediction methods for oscillatory-type alpha changes that are simple enough to be used in preliminary design. The needed information could be obtained through static and dynamic tests with models having varying static cambers $\Delta\alpha_c$ covering the desired range for $\dot{\alpha}c/U_\infty$. With the effect of $\Delta\alpha_c$ determined in static tests, dynamic test results over the needed range of $\dot{\alpha}c/U_\infty$ should define the time–history effects.

These results for pitching delta wings warn the vehicle designer that a wing with swept leading edges could be a source of strong control/vehicle-dynamics coupling for aircraft performing supermaneuvers.[12]

## Conclusions

An analysis of the experimentally observed dissimilar effects of pitch rate on delta wing vortex breakdown can be understood by applying previously developed time-lagged dynamically equivalent steady flow concepts.

1) The flow physics are defined by the initial static flow conditions and the pitch-rate-induced effects on the effective apex angle of attack $\alpha_A$ and the pitch-rate-induced camber effect $\Delta\alpha_c$. Both $\alpha_A$ and $\Delta\alpha_c$ are associated with time–history effects that often can be approximated by the effect of a constant time lag.

2) The flowfield characteristics are relatively uncomplicated for oscillatory motions, where the transient effects associated with ramp motions become insignificant.

## References


[1]Atta, R., and Rockwell, D., "Leading-Edge Vortices due to Low Reynolds Number Flow Past a Pitching Delta Wing," *AIAA Journal*, Vol. 28, No. 6, 1990, pp. 995–1004.

[2]Guglieri, G., Onorato, M., and Quagliotti, F., "Breakdown Analysis on Delta Wing Vortices," *Zeitschrift für Flugwissenschaften und Weltraumforschung*, Vol. 16, Heft 4, 1992, pp. 226–230.

[3]Ericsson, L. E., "Vortex Breakdown Dynamics on Pitching Delta Wings," AIAA Paper 95-1777, June 1995.

[4]Thompson, S. A., Bathill, S. M., and Nelson, R. C., "Separated Flow Field on a Slender Wing Undergoing Transient Pitching Motions," *Journal of Aircraft*, Vol. 28, No. 8, 1991, pp. 489–495.

[5]Lambourne, N. C., Bryer, D. W., and Maybrey, J. F. M., "Pressure Measurements on a Model Delta Wing Undergoing Oscillatory Deformation," National Physics Lab., Aero Rept. 1314, Aeronautical Research Council, UK, March 1970.

[6]Lowson, M. V., "Some Experiments with Vortex Breakdown," *Journal of the Royal Aeronautical Society*, Vol. 68, May 1964, pp. 343–346.

[7]Jenkins, J. E., Myatt, J. H., and Hanff, E. S., "Body-Axis Rolling Motion Critical States of a 65-Degree Delta Wing," AIAA Paper 93-0621, Jan. 1993.

[8]Ericsson, L. E., "Flow Physics of Critical States for Rolling Delta Wings," *Journal of Aircraft*, Vol. 32, No. 3, 1995, pp. 603–610.

[9]Atta, R., and Rockwell, D., "Hysteresis of Vortex Development and Breakdown on an Oscillating Delta Wing," *AIAA Journal*, Vol. 25, No. 11, 1987, pp. 1512, 1513.

[10]Reynolds, G. A., and Abtahi, A. A., "Instabilities in Leading-Edge Vortex Development," AIAA Paper 87-2424, Aug. 1987.

[11]Lowson, M. V., and Rily, A. J., "Vortex Breakdown Control by Delta Wing Geometry," AIAA Paper 94-3487, Aug. 1994.

[12]Ericsson, L. E., and Beyers, M. E., "Fluid/Motion Coupling in Conceptual Supermaneuvers," AIAA Paper 96-0787, Jan. 1996.