[8]Meadows, K., Kumar, A., and Hussaini, M. Y., "A Computational Study on the Interaction Between a Vortex and a Shock Wave," *AIAA Journal*, Vol. 29, No. 2, 1990, pp. 174–179.

[9]Wang, J. C. T., and Windhopf, G. F., "Numerical Simulation of Blast Flowfields Using a High Resolution TVD Finite Volume Scheme," *Computers and Fluids*, Vol. 18, No. 1, 1990, pp. 103–137.

Active Control of Vortex Breakdown over a Delta Wing

I. Gursul,* S. Srinivas,† and G. Batta*
University of Cincinnati, Cincinnati, Ohio 45221-0072

Introduction

THE objective of this study is to accomplish active control of vortex breakdown over delta wings. The first step in this effort is to identify a physical quantity that indicates the existence of vortex breakdown and can be used as a feedback signal for active control. Previous studies[1,2] suggest that pressure fluctuations induced by the helical mode instability of vortex breakdown is a good candidate. Measurement of pressure fluctuations at a single location on the wing surface can be sufficient for control purposes. The variation of the amplitude of pressure fluctuations (or rms value of pressure) with the breakdown location seems monotonic.[2] Hence, in this study, the rms value of pressure was chosen as the control variable, and a feedback control strategy was considered.

The second element in active control of vortex breakdown is to identify a flow controller to influence the vortex breakdown location. Several methods were shown to delay vortex breakdown. Blowing and suction in the tangential direction along the leading edge,[3,4] suction applied around the vortex axis,[5,6] and use of leading-edge flaps[7] are among them. For most of the techniques mentioned, however, the relationship between the control parameter and the vortex breakdown location is unknown or undesirable (i.e., not monotonic). A desirable controller should have a monotonic relationship between the control parameter and breakdown location. Sweep angle has such a relationship. Therefore, variable sweep angle control was employed in this study. The relationship between the sweep angle and vortex breakdown location is very well known from static experiments.

A delta wing with variable sweep was fabricated (see Fig. 1a). Measured rms value of pressure coefficient at a fixed point close to the trailing edge ($x/c = 0.94$, $y/c = 0.27$) is shown as a function of angle of attack and sweep angle in Fig. 1b. The flat region near $\Lambda = 70$ deg shows the pressure fluctuation level in the absence of the vortex breakdown over the wing ($C_p \cong 0.05$). With increasing angle of attack or decreasing sweep angle, the vortex breakdown moves over the wing as the rms pressure level increases and finally reaches a saturation. This approximate monotonic relation between the sweep angle Λ and rms C_p suggests that a feedback control may be feasible. The increase in pressure fluctuations with the decreasing sweep angle is due to the increasing length of the breakdown region over the wing, as well as increasing circulation of the leading-edge vortex.[8]

An important consideration for the feedback control is the system dynamic response. It is well known that the dynamic response of the vortex breakdown location in unsteady flows is characterized by time-lag effects. It was suggested that the response of the breakdown location is similar to that of a first-order system.[8] Estimated values of the time constant for different types of motion are summarized in Ref. 8. Flow-visualization experiments[7] for variable sweep angle in a water channel showed that the normalized time constant is $\tau U_\infty/c = 2$–7. The idealization as a first-order system suggested that either proportional or integral control (or a combination of both) could be suitable for this application.

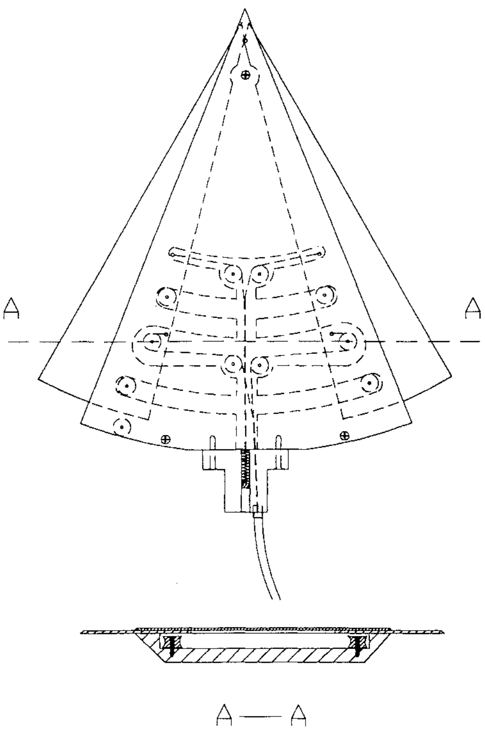

Fig. 1a Schematic of variable sweep delta wing.

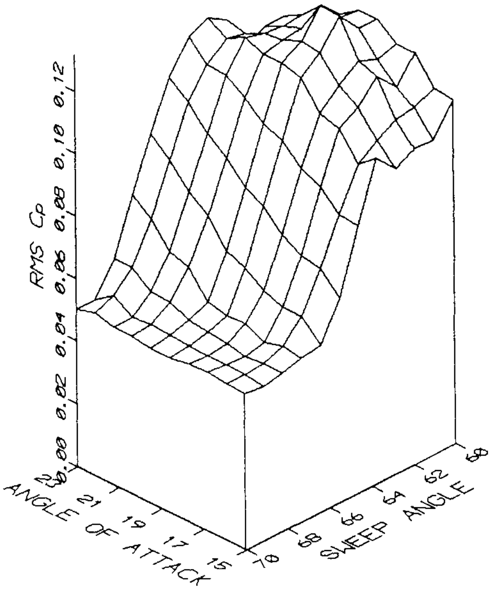

Fig. 1b RMS value of pressure coefficient as a function of angle of attack and sweep angle.

Experimental Setup

Experiments were carried out in a closed-circuit wind tunnel with a cross-sectional area of 61 by 61 cm. Details of the experimental setup and model can be found in Ref. 8. The chord length of the wing shown in Fig. 1a was $c = 268$ mm and the Reynolds number was $Re = 190{,}000$. The range of sweep angle was from $\Lambda = 60$ to $\Lambda = 70$ deg. Two thin plates were used to change the sweep angle. The motion of the plates was guided with a cable-pulley-pin system. A bicycle brake cable, whose sheath was fixed near the trailing edge and outside the wind tunnel, was attached to a drum, which was driven by a dc motor servo system. This flexible system allowed the use of variable sweep even for a pitching motion of the delta wing. The unsteady surface pressure was measured by a high-sensitivity

---

Received Dec. 12, 1994; revision received May 18, 1995; accepted for publication June 1, 1995. Copyright © 1995 by the authors. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.

*Assistant Professor, Department of Mechanical, Industrial and Nuclear Engineering.

†Graduate Student, Department of Mechanical, Industrial and Nuclear Engineering.

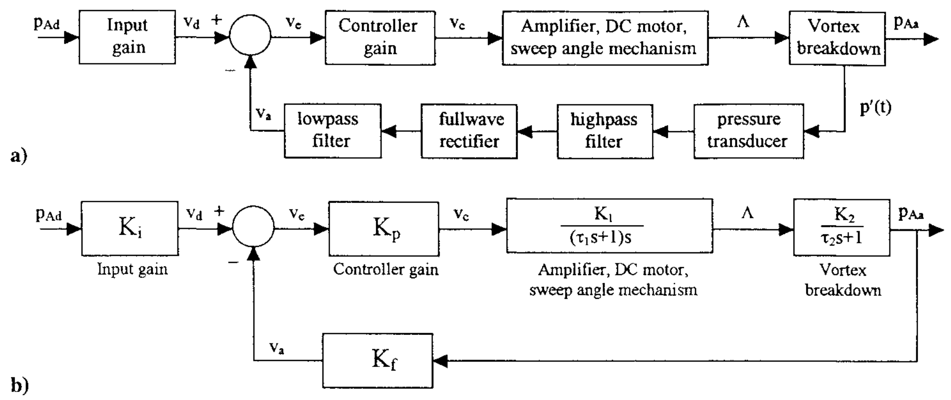

Fig. 2 Block diagram: a) feedback control system showing signal conditioning components and b) with transfer functions.

piezoelectric transducer (PCB model 103A). The measurement location was $x/c = 0.94$, $y/c = 0.27$, which was chosen based on previous measurements.[1] The active control experiments were conducted both for a stationary and a pitching delta wing. The pitching mechanism was similar to the one used by LeMay et al.[9] The angle of attack was varied between 15 and 23 deg. A variable speed dc motor and a speed controller were used to drive the pitching mechanism.

Since the rms value of pressure was chosen as the control variable, an approximation for the rms pressure was necessary in a real-time control loop. The raw pressure fluctuation signal $p'(t)$ was rectified and low-pass filtered.[8] The latter quantity is denoted by p_A, which represents the amplitude of the pressure fluctuations. The signal $p_A(t)$ was used as the control variable. The overall objective of the control system was translated into a control objective of maintaining a particular value of pressure amplitude $p_A(t)$. The implementation of the controller can be more easily understood by considering the block diagram representation of the system as shown in Fig. 2a. The plant in this control system consists of two parts: the mechanical position dynamics of the sweep angle mechanism and the vortex breakdown process. The pressure amplitude $p_A(t)$ was obtained by rectifying and low-pass filtering, after the signal from the pressure transducer was passed through a high-pass filter. The rectification was obtained using a full-wave bridge rectifier. The signal conditioning circuits and the feedback control system for the sweep angle were implemented using operational amplifiers. These circuits were constructed on a breadboard. The block diagram of the feedback control system with the transfer functions is shown in Fig. 2b. The power amplifier, dc motor, and sweep angle mechanism were modeled as a dc motor with a directly coupled inertia. Frequency response tests of the sweep angle mechanism indicate that this is a reasonable approximation. The transfer function for this model is shown in Fig. 2b. The time constant τ_1 was estimated from the step response tests as $\tau_1 \cong 0.25$ s, $(9.3c/U_\infty)$. As indicated earlier, the vortex breakdown process is modeled as a first-order dynamic system with time constant τ_2. The time constant τ_2 was estimated from the water channel experiments[7] as $\tau_2 = (2\text{–}7)c/U_\infty$.

Since the sweep angle positioning mechanism provides an integral relationship in the forward path, an integral controller for the overall control system was relatively easy to implement. In addition, integral control has the advantage of small steady-state error. The only parameter needed in the controller design was the gain K_p. Since specific values of the plant parameters were not easily obtained, the gain K_p was chosen by trial and error.

Results

First, the active control experiments were conducted for the stationary delta wing at angle of attack $\alpha = 19$ and 23 deg. The results for $\alpha = 23$ deg are shown in Fig. 3. Initially, the sweep angle was set to $\Lambda = 60$ deg and the desired voltage v_d (corresponding to a desired pressure amplitude p_{Ad}) was chosen as 1.0 V. For this value of sweep angle, the vortex breakdown location was over the wing and closer to the apex. In Fig. 3, plots of pressure fluctuation $p'(t)$, feedback voltage $v_a(t)$, and sweep angle $\Lambda(t)$ are shown. At around $t = 5$ s, the feedback control was turned on. Note that the

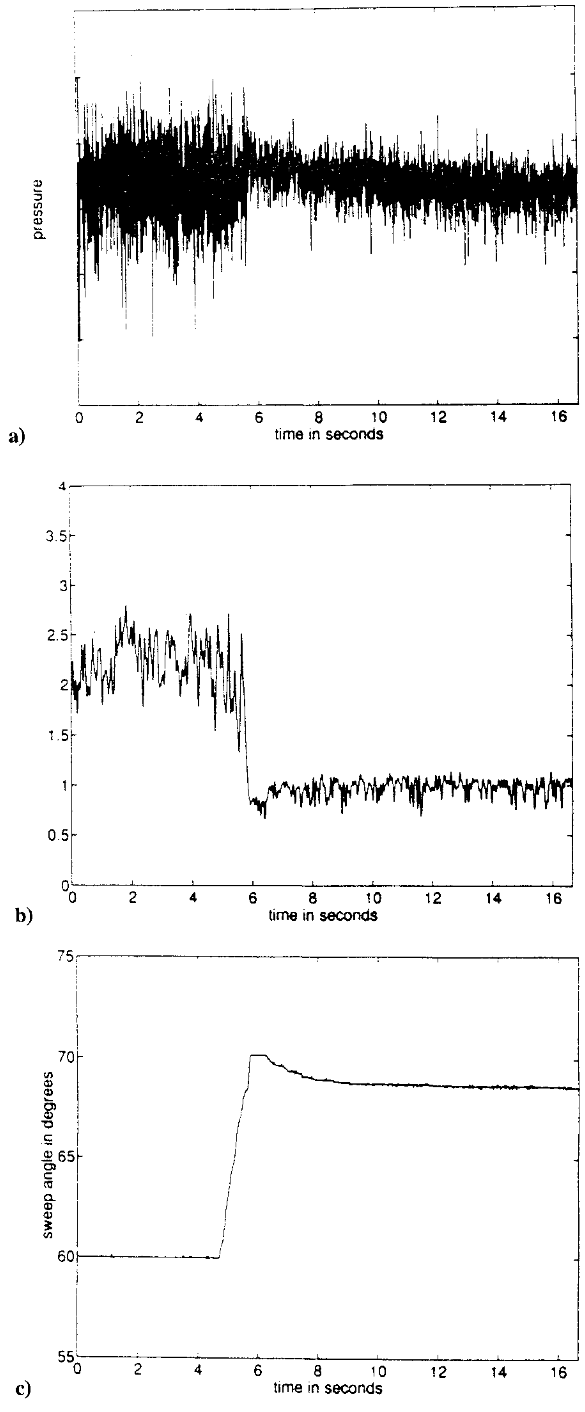

Fig. 3 Variation of a) pressure fluctuation $p'(t)$, b) feedback voltage $v_a(t)$, and c) sweep angle $\Lambda(t)$ as a function of time, $\alpha = 23$ deg.

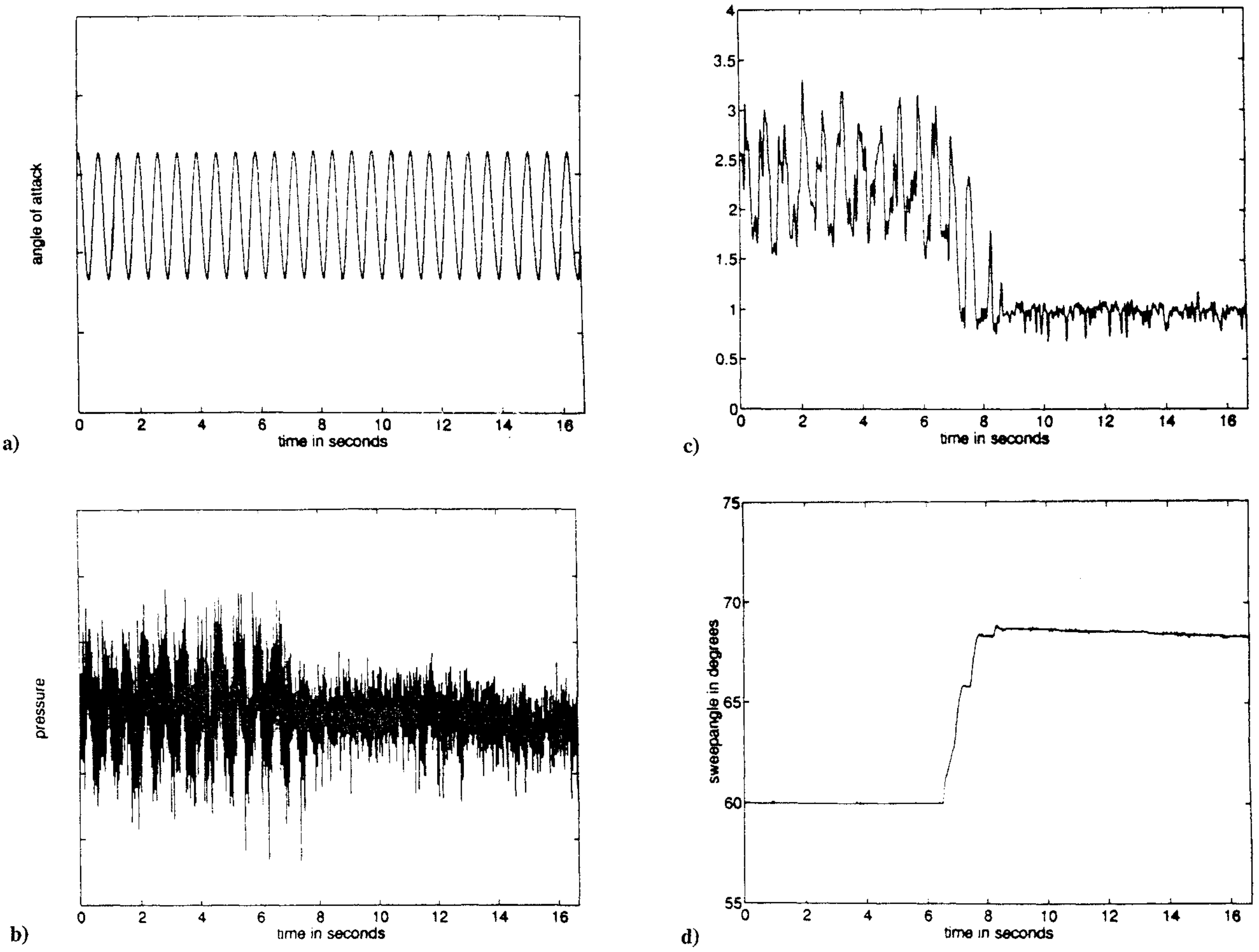

Fig. 4 Variation of a) angle of attack $\alpha(t)$, b) pressure fluctuation $p'(t)$, c) feedback voltage $v_a(t)$, and d) sweep angle $\Lambda(t)$ as a function of time, $\alpha(t) = 19 + 4\cos(\omega t)$ (deg), $k = \omega c/2U_\infty = 0.12$.

sweep angle $\Lambda(t)$ increases and becomes nearly constant around $\Lambda \cong 68.5$ deg after a small overshoot. This new sweep angle corresponds to a case where the breakdown location is downstream of the wing. The decrease in raw pressure fluctuations and feedback voltage accompany the variation of sweep angle. Similar results were obtained for $\alpha = 19$ deg. Experiments for different values of the desired voltage v_d, which represents the desired pressure amplitude, were carried out. When this parameter was increased to $v_d = 1.5$ V, the overshoot of the sweep angle was not observed.

The active control experiments for the pitching delta wing were conducted in a similar way. As the delta wing was pitched periodically between 15 and 23 deg, i.e., $\alpha(t) = 19 + 4\cos(\omega t)$ (deg), the initial sweep angle was set to 60 deg. For this range of angle of attack, the vortex breakdown was over the wing during the whole cycle. The plots of angle of attack $\alpha(t)$, pressure fluctuation $p'(t)$, feedback voltage $v_a(t)$, and sweep angle $\Lambda(t)$ are shown in Fig. 4 for a desired voltage $v_d = 1.0$ V and a reduced frequency $k = \omega c/2U_\infty = 0.12$, where ω is the radial frequency of the pitching motion. Again, the feedback control was turned on suddenly. It is seen that the sweep angle $\Lambda(t)$ increases and becomes nearly constant around a new value for which the breakdown location is downstream of the wing. It is also seen that the magnitude of pressure fluctuations decreases substantially as a result of feedback control.

Conclusions

It is shown that pressure fluctuations induced by the helical mode instability of vortex breakdown can be used to control the vortex breakdown location. Measurement of pressure fluctuations at a single location on the delta wing is sufficient for this purpose. The monotonic variation of the amplitude of the pressure fluctuations with vortex breakdown location makes the feedback control possible. Based on previous experiments on the dynamic response of vortex breakdown location, the system was idealized as a first-order system, and integral control was used. The active control of vortex breakdown was achieved for stationary as well as pitching delta wings.

Acknowledgment

This research was supported by the Air Force Office of Scientific Research Grant F49620-92-J-0532.

References

[1] Gursul, I., "Unsteady Flow Phenomena over Delta Wings at High Angle of Attack," *AIAA Journal*, Vol. 32, No. 2, 1994, pp. 225–231.

[2] Gursul, I., and Yang, H., "Vortex Breakdown over a Pitching Delta Wing," AIAA Paper 94-0536, Jan. 1994.

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

[4] 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. 1177–1186.

[5] Werle, H., "Sur l'eclatement des tourbillons d'apex d'une aile delta aux fibles vitesses," *La Recherche Aeronautique*, No. 74, Jan.–Feb. 1960, pp. 23–30.

[6] Parmenter, K., and Rockwell, D., "Transient Response of Leading-Edge Vortices to Localized Suction," *AIAA Journal*, Vol. 28, No. 6, 1990, pp. 1131–1133.

[7] Gursul, I., Yang, H., and Deng, Q., "Control of Vortex Breakdown with Leading-Edge Devices," AIAA Paper 95-0676, Jan. 1995.

[8] Srinivas, S., Gursul, I., and Batta, G., "Active Control of Vortex Breakdown over Delta Wing," AIAA Paper 94-2215, June 1994.

[9] LeMay, S. P., Batill, S. M., and Nelson, R. C., "Vortex Dynamics on a Pitching Delta Wing," *Journal of Aircraft*, Vol. 27, No. 2, 1990, pp. 131–138.