AIAA Journal
Vol. 42, No. 2, February 2004

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed six manuscript pages and three figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Experimental Studies on Control of Delta Wing Aerodynamics

Jinjun Wang* and Yan Xu†
Beijing University of Aeronautics and Astronautics, 100083 Beijing, People's Republic of China

Introduction

It has been found that swept wing aircraft, especially small-aspect-ratio aircraft, have little wave drag at supersonic speed. However, this wing has a low lift coefficient and is difficult to control. The flow leeward of the delta wing is very complicated at high angles of attack, cross-flow separation, and vortex breakdown. Vortex breakdown has adverse effects not only because of a decrease in the lift but also because of wing rock induced by the asymmetry of vortex breakdown.

The methods for controlling vortex breakdown at high angles of attack include blowing or suction, cyclic blowing and suction, trailing-edge jets, and deployment of control surfaces.[1–5] Recently, an apex flap has been shown to be a useful delta wing control device to postpone vortex breakdown.[6] This topic has been investigated by some scholars through flow visualization in a water tunnel and pressure measurement in a wind tunnel. Lowson and Riley[7] pointed out that a drooping apex flap could delay vortex breakdown. It was found to provide about 1% chord movement in the vortex breakdown position for a 1-deg change in flap angle. Those tests were done with an apex flap of 40% chord on a 75-deg delta wing.[8] The results indicated that the optimum deflection angle, i.e., the maximum breakdown delay, corresponds to $B = 15$ deg, and the same configuration appears to be equally efficient in controlling breakdown during pitch-up maneuvers.

The present work focuses on the effect of an apex flap on aerodynamic characteristics of the delta wings. The experiments were conducted in a wind tunnel, and it is expected that the experimental results would offer further insight into the effects of an apex flap on the aerodynamic performance of a delta wing and provide a basis for an engineering application.

Facilities and Instrumentation

Tests were conducted in an open wind tunnel with a test section of 1.02×0.76 m. A six-component balance was employed in the wind tunnel to measure forces and moments of the wings. In this research, four delta wing models of plexiglass construction with the same sweep angle Λ of 70 deg and the same chord length c of 0.25 m were utilized. The model blockage is 2.9% for the wind tunnel, and so it is not necessary to modify the blockage effects. The thickness of the model in the wind tunnel is 5 mm. The lee surfaces were flat, whereas the leading edges were beveled at 45 deg on the windward side. The section of the wing from the apex to positions at 20%, 30%, 40%, and 50% of the chord length was hinged to deflect down relative to the rest of the wing, and the drooping angle was denoted by the symbols B_1, B_2, B_3, and B_4, respectively. This flap angle was varied from 0 to 30 deg. The model is shown schematically in Fig. 1. The freestream velocity is 20 m/s, which results in a chord Reynolds number of $Re = 3.16 \times 10^5$.

Results and Discussion

Effect of Apex Flap on Aerodynamics of Delta Wing

The effect of the apex flap on the aerodynamic performance of the delta wing is demonstrated for a 30%c apex flap. When the flap is deflected downward, the effective angle of attack decreases for the entire delta wing; thus lift increases at high angles of attack. Figure 2 shows that the lift coefficient C_L increases drastically with the flap angle; meanwhile, the stall angle is delayed from 35 to 40 deg when B_2 is beyond 24 deg. Figure 3 shows that the drag coefficient C_D is barely influenced.

It can be seen from Fig. 4 that in the case of $\alpha = 20$ and 25 deg, the relative increment of lift-to-drag ratio $\Delta k/k$ has maximum values at about $B_2 = 20$ deg. When the angle of attack increases beyond 25 deg, the curve of the relative increment of the lift-to-drag ratio rises always in the total range of flap deflection tested. It has been suggested that the apex flap still produces a positive effect on the lift-to-drag ratio at high angles of attack.

The apex flap has a significant effect on rolling moment. Figure 5 shows that the rolling moment C_R decreases in the range of angle

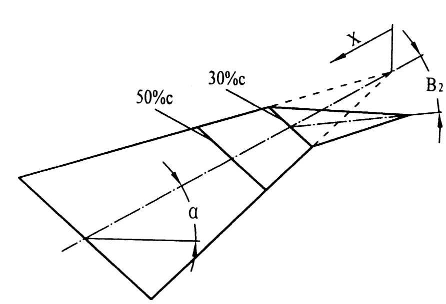

Fig. 1 Delta wing model with apex flaps.

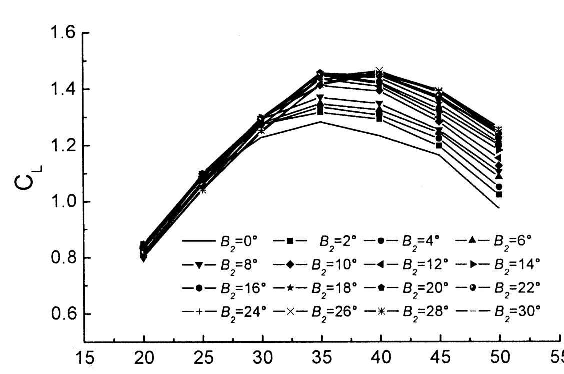

Fig. 2 Effect of 30%c flap (B_2) on lift coefficient.

Received 20 August 2002; revision received 27 March 2003; accepted for publication 21 May 2003.

*Professor, Fluid Mechanics Institute; jjwang@buaa.edu.cn.
†Postgraduate Student, Fluid Mechanics Institute.

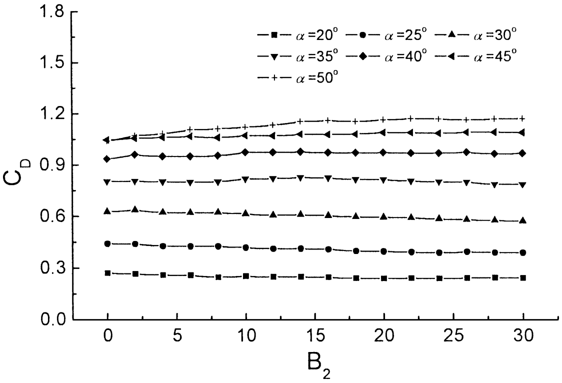

Fig. 3 Effect of 30%c flap (B_2) on drag coefficient.

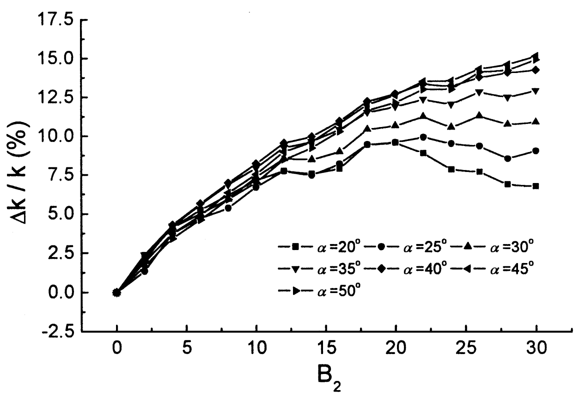

Fig. 4 Effect of 30%c flap (B_2) on lift-to-drag ratio.

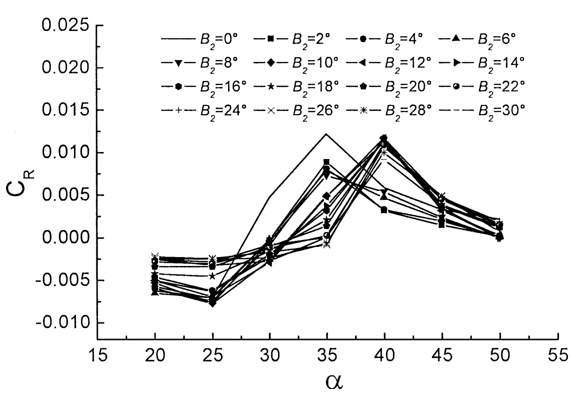

Fig. 5 Effect of 30%c flap (B_2) on rolling moment coefficient.

of attack from 27 to 37 deg in the negative apex flap deflection. A peak of the rolling moment corresponding to $B_2 > 10$ deg is shifted to an angle of attack 5 deg higher than in the baseline case. The peak value of rolling moment is higher than that of $B_2 \leq 10$ deg but lower than that of the baseline case. This may be caused by the vortex originating from the location of flap deflection at a high angle of attack. Hence, it seems that the apex flap can be used to eliminate rolling instability and suppress wing rock. It is also found that the negative pitching moment increases as the angle of deflection increases when the angle of attack is beyond 25 deg; it has been suggested that an apex flap can enhance the stability of pitch-up.

Effect of Flap Length on Aerodynamics of Delta Wing

As shown in Fig. 2 for a delta wing with 30%c apex flap the apex flap can delay the stall angle of the delta wing about 5 deg when the angle of the apex flap is greater than $B_2 = 24$ deg. In this Note, four different lengths of flaps are used to investigate their effect on delta wing aerodynamics, and it has been found that the stall angle has been shifted from 35 to 40 deg in comparison with the delta wing without an apex flap, and the corresponding flap deflection angles are $B_1 = 30$ deg, $B_2 = 24$ deg, $B_3 = 8$ deg, and $B_4 = 6$ deg for the four different apex flap tested, respectively. In other words, it can be concluded that, in order to cause a 5-deg shift in stall angle, the minimum value of the flap angle decreases with apex flap lengths. Moreover, for a delta wing with 50%c flap, when $B_4 \geq 26$ deg, the stall angle may be delayed up to 45 deg; this means that the flap can result in a 10-deg shift in the stall angle of the delta wing relative to the wing without an apex flap.

Table 1 Effect of flap length on delaying the appearance of peak rolling moment

	Angles of attack corresponding to peak rolling moment			
B	35 deg	40 deg	45 deg	>50 deg
B_1	0~16	18~30		
B_2	0~10	12~30		
B_3	0~4	6~22	24~28	30
B_4	0~4	6~18	20~22	24~30

Table 1 shows the range of flap angle, which corresponds to the peak of rolling moment. It can be deduced that the peak of rolling moment is delayed to occur at the higher angle of attack and the rolling moment is more sensitive to the apex flap angle than the lift coefficient is.

The experimental results indicated that the 20%c apex flap increases lift more than the other flaps at the angle of attack of 20 deg, whereas the 50%c apex flap has a better effect on lift than the other smaller flaps at $\alpha = 45$ deg. This demonstrates that smaller flaps are more effective than bigger ones at increasing lift at a low angle of attack. However, the bigger flaps are better at high angles of attack.

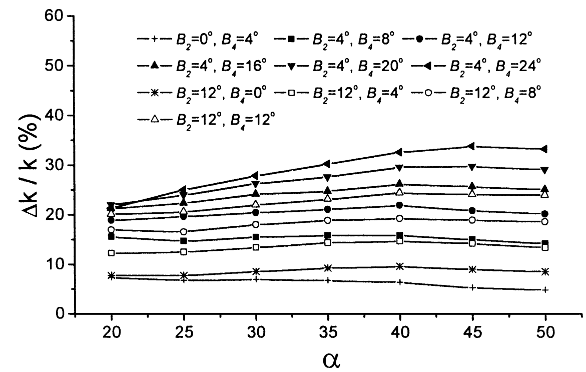

Fig. 6 Variation of lift-to-drag ratio in the case of a combination of two flaps, B_2 and B_4, as a function of angle of attack.

Effect of Combination of Two Flaps

The increment of lift-to-drag ratio is showed in Fig. 6. Obviously, the lift-to-drag ratio, for the case of combination $B_2 = 12$ deg with $B_4 = 4$ deg, increases much more than that of $B_2 = 12$ deg or $B_4 = 4$ deg, respectively. This suggests that the combination of two flaps is more effective than the single flap in delaying vortex breakdown and promoting lift-to-drag ratio due to the decrease in attack angles, which is in accordance with the results obtained by Lambourne and Bryer[9] for a cambered delta wing.

Conclusions

The drooping apex flap, effectively reducing the angle of attack of the portion of the wing closest to the apex, can delay vortex breakdown, promote lift-to-drag ratio, and postpone the onset of stall. The stalling angle increases as the length of the apex flap increases, and for the 50%c apex flap, a shift in angle of stall of around 10 deg is obtained, meaning that the apex flap can improve the rolling moment and enhance the stability of pitch-up greatly. The effectiveness of the bigger flap on increasing lift at low angles of attack was surpassed by the smaller flap, but the inverse is true at high angles of attack. Moreover, the improvements in the lift coefficient for the combination of the two apex flaps were more effective than for the single flap.

Acknowledgment

The project was supported by the Aeronautic Science Foundation of China.

References

[1]Wood, N. J., and Roberts, L., "The Control of Vortical Lift on Delta Wings by Tangential Leading-Edge Blowing," AIAA Paper 87-0158, Jan. 1987.

[2]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.

[3]Rinoie, K., and Stollery, J. L., "Experimental Studies of Vortex Flaps and Vortex Plates," *Journal of Aircraft*, Vol. 31, No. 2, 1994, pp. 322–329.

[4]Srigrarom, S., and Kurosaka, M., "Shaping of Delta-Wing Planform to Suppress Vortex Breakdown," *AIAA Journal*, Vol. 38, No. 1, 2000, pp. 183–186.

[5]Helin, H. E., and Watry, C. W., "Effects of Trailing-Edge Jet Entrainment on Delta Wing Vortices," *AIAA Journal*, Vol. 34, No. 7, 1996, pp. 802–804.

[6]Rao, D. M., and Buter, T. A., "Experimental and Computational Studies of a Delta Wing Apex Flap," AIAA Paper 83-1815, July 1983.

[7]Lowson, M. V., and Riley, A. J., "Vortex Breakdown Control by Delta Wing Geometry," *Journal of Aircraft*, Vol. 32, No. 4, 1995, pp. 832–838.

[8]Klute, S. M., Rediniotis, O. K., and Telionis, D. P., "Flow Control over a Maneuvering Delta Wing at High Angles of Attack," *AIAA Journal*, Vol. 34, No. 4, 1996, pp. 662–668.

[9]Lambourne, N. C., and Bryer, D. W., "The Bursting of Leading Edge Vortices—Some Observations and Discussion of the Phenomenon," Aeronautical Research Council, Repts. and Memoranda, No. 3282, 1961, pp. 1–37.

A. Plotkin
Associate Editor

Three-Dimensional Benchmark Problem for Broadband Time-Domain Impedance Boundary Conditions

Shi Zheng* and Mei Zhuang†
Michigan State University, East Lansing, Michigan 48824

Introduction

AEROACOUSTIC problems in liner technology are an important category of the application of computational aeroacoustics (CAA). Because of the limitations of the frequency-domain simulations, the time-domain impedance boundary conditions in CAA applications have been exploited in the past few years. Because liner impedance is conventionally defined in frequency domain, it is desirable to convert characteristics of impedance in the frequency domain into the time domain so that the information can serve as a well-posed boundary condition for the linearized Euler equations. Several approaches of converting the frequency-domain impedance boundary condition into the time domain have been carried out,[1–4] one of which was developed by Tam and Auriault.[1] They have proved the well-posednature and stability of their impedance boundary conditions, but have not tested their boundary conditions in a dimensionality higher than one. In this Note, a three-dimensional acoustic problem with an impedance boundary is proposed. The analytical solution is derived and then is used to test the numerical solution due to such a time-domain impedance boundary condition.

Test Problem Formulation

The test problem is shown in Fig. 1. The domain of interest lies in the ranges of $-\infty < x < \infty$, $-\infty < y < \infty$, and $z \geq 0$. A liner with uniform impedance $Z(\omega) = \hat{p}(\omega)/\hat{v}_n(\omega)$ is applied at $z = 0$, where $\hat{p}$ and $\hat{v}_n$ are acoustic pressure and particle velocity $\hat{v}_n$ normal to the liner (positive when pointing into the liner) in the frequency domain. A spherical Gaussian acoustic pressure pulse $p_0(R) = \exp(-BR^2)$ is initially introduced with zero initial velocity components, where constant $B > 0$ and R is the distance to the pulse center at $S(0, 0, z_S)$. Note that all of the quantities in this Note are nondimensionalized such that the speed of sound is unity.

Analytical Solution

The analytical solution of the test problem is considered to be the superposition of three component waves, that is, the outgoing wave, which diverges from the sphere center; the incoming wave, which converges to the sphere center; and the reflected wave by the impedance boundary. A broadband incident wave needs to be decomposed into harmonic waves, and a nonplane incident wave needs to be decomposed into plane waves. Then the reflection of each of the harmonic plane incident waves by the impedance boundary can be determined. The total reflected wave is in a form of an integral of the reflected harmonic plane waves. This is the general idea for deriving the analytical solution to our test problem.

The outgoing and incoming waves in free space with the same initial condition can be determined, in terms of the velocity potential φ defined by $\nabla\varphi = \boldsymbol{v}$ with spherical symmetry,[5] to be

$$\varphi_{\text{out}}(R, t) = f(R - t)/R \tag{1}$$

$$\varphi_{\text{in}}(R, t) = -f(R + t)/R \tag{2}$$

where $R = \sqrt{[x^2 + y^2 + (z - z_s)^2]}$ and f is determined from the initial condition to be $f(r) = -\exp(-Br^2)/(4B)$, for $-\infty < r < \infty$.

For the test problem, the outgoing and incoming waves are not exactly the same as the given free space solutions. This is because the actual initial condition is not a complete spherical Gaussian pulse, part of which is outside the semi-infinite space. However, if the center of the spherical pulse is far away from the impedance boundary, the outside portion of the initial pulse will be of very small amplitude and, thus, insignificant to the whole problem. Therefore, we can safely assume a complete initial spherical Gaussian pulse for the test problem and approximate its outgoing and incoming waves with the free space solution in Eqs. (1) and (2). Such treatment will greatly simplify the analysis. The reflected wave is determined by considering the incident (outgoing) wave φ_{out} in Eq. (1) being reflected by the impedance boundary. As stated earlier, the broadband spherical outgoing wave must be decomposed into harmonic plane components to study the effects of the impedance boundary. This decomposition process is done in the following two steps, which can be done in reverse order:

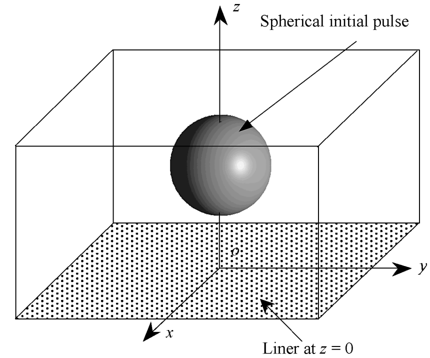

Fig. 1 Schematic of the test problem.

Received 3 August 2002; revision received 5 June 2003; accepted for publication 20 July 2003.

*Graduate Research Assistant, Department of Mechanical Engineering.

†Associate Professor, Department of Mechanical Engineering. Senior Member AIAA.