JOURNAL OF AIRCRAFT
Vol. 31, No. 3, May–June 1994

Lift Enhancement of an Airfoil Using a Gurney Flap and Vortex Generators

Bruce L. Storms*
Sterling Software, Moffett Field, California 94035
and
Cory S. Jang†
California Polytechnic State University, San Luis Obispo, California 93407

Experimental measurements of surface pressure distributions and wake profiles were obtained for an NACA 4412 airfoil to determine the lift, drag, and pitching-moment coefficients for various configurations. The addition of a Gurney flap increased the maximum lift coefficient from 1.49 up to 1.96, and decreased the drag near the maximum lift condition. There was, however, a drag increment at low-to-moderate lift coefficients. Additional nose-down pitching moment was also generated by increasing the Gurney flap height. Good correlation was observed between the experiment and Navier-Stokes computations of the airfoil with a Gurney flap. Two deployable configurations were also tested with the hinge line forward of the trailing edge by one and 1.5 flap heights, respectively. These configurations provided performance comparable to that of the Gurney flap. The application of vortex generators to the baseline airfoil delayed boundary-layer separation and yielded an increase in the maximum lift coefficient of 0.34. In addition, there was a significant drag penalty associated with the vortex generators, which suggests that they should be placed where they will be concealed during cruise. The two devices were also shown to work well in concert.

Nomenclature

C_d = section drag coefficient, d/qc
C_l = section lift coefficient, l/qc
C_m = section pitching-moment coefficient, m/qc^2
C_p = pressure coefficient, $(p - p_\infty)/q$
c = reference airfoil chord, ft
d = section drag, lbf
h = flap height, ft
L/D = lift-to-drag ratio
l = section lift, lbf
m = section pitching moment, ft-lbf
p = static pressure, psi
q = dynamic pressure, $\frac{1}{2}\rho V^2$, psi
V = freestream velocity, ft/s
x = axial distance from airfoil leading edge, ft
α = angle of attack, deg
δ = boundary-layer thickness, in.
ρ = density of air, lbm/ft^3

Subscripts
max = maximum value
∞ = freestream value

Introduction

THE payload and range of subsonic transports are dictated, and often limited, by the performance of their high-lift systems. These systems are generally quite complex, consisting of a leading-edge slat and two or three trailing-edge flaps. The high maintenance and weight penalty associated with such configurations have provided an impetus for the design of mechanically simpler high-lift systems with no degradation in performance. However, to maintain the high lift coefficients required for approach and landing, new technology is needed to provide lift enhancement and separation control.

One candidate technology is the Gurney flap which consists of a small plate, on the order of 1–2% of the airfoil chord in height, located at the trailing edge perpendicular to the pressure side of the airfoil (Fig. 1). This device was originally used on the airfoils of performance race cars to increase the down force for the lateral traction required during high-velocity turns. Liebeck[1] tested a 1.25% chord Gurney flap on a New-

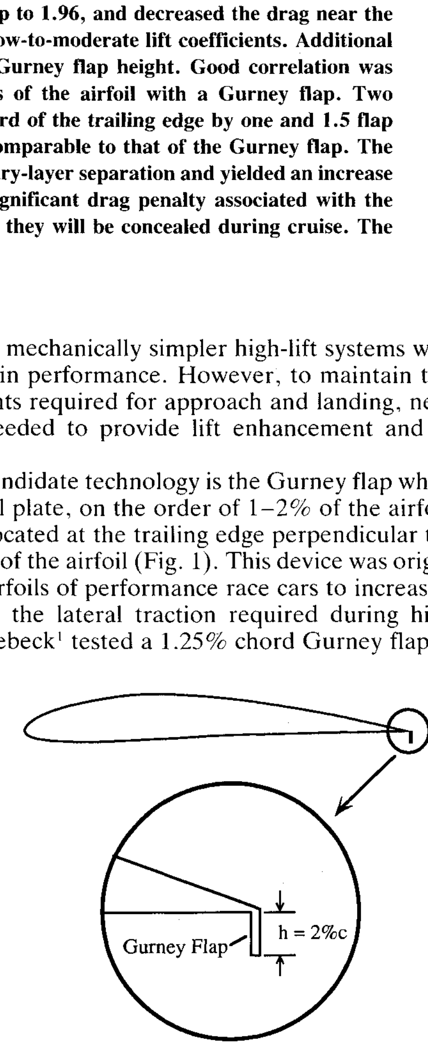

Fig. 1 2% chord Gurney flap on a 4412 airfoil.

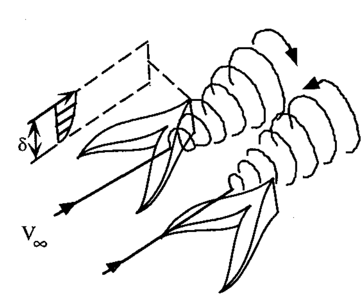

Fig. 2 Submerged vortex generators detailed in Ref. 9.

Presented as Paper 93-0647 at the AIAA 31st Aerospace Sciences Meeting, Reno, NV, Jan. 11–14, 1993; received Feb. 22, 1993; revision received April 19, 1993; accepted for publication April 19, 1993.

*Aerospace Engineer, Fixed Wing Aerodynamics Branch, MS 247-2, NASA Ames Research Center. Member AIAA.
†Graduate Student, Aeronautical Engineering Department. Student Member AIAA.

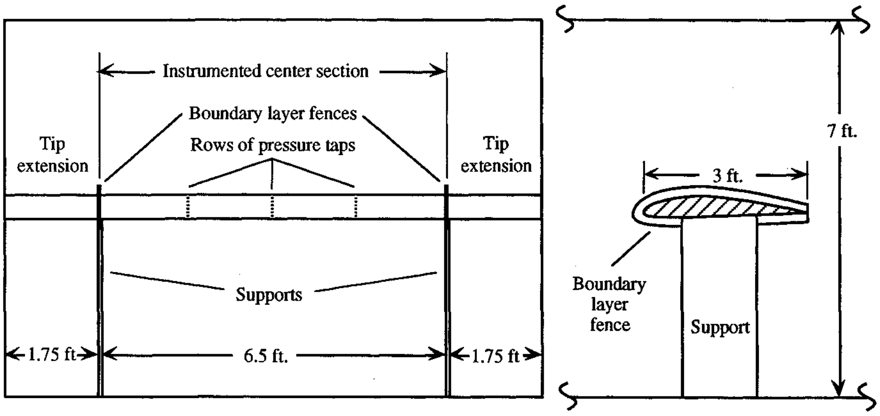

Fig. 3 NACA 4412 in the NASA Ames 7- by 10-ft Wind Tunnel test section.

man airfoil which resulted in an increase in lift and a slight reduction in drag. Larger lift increments were observed for greater flap heights, but the drag increased noticeably beyond heights of approximately 2% chord. Experimental investigations incorporating a Gurney flap on the trailing element of multielement race-car airfoils were later conducted by Katz and Largman[2] and Katz and Dykstra.[3] Both investigations reported a substantial increase in lift (as much as 50% using a 5% chord Gurney flap), but the corresponding L/D was reduced over the design angle-of-attack range.

A computational study of an NACA 4412 airfoil with a Gurney flap was conducted by Jang et al.[4] An incompressible Navier-Stokes code was used to compute the flowfield about the airfoil with Gurney flap heights ranging from 0.5 to 3.0% chord. With the addition of a Gurney flap, the computations predicted a significant lift increment that increased with flap size, although not linearly. The computed pressure distributions indicated increased loading along the entire airfoil when compared with the baseline, particularly at the suction peak and near the trailing edge. The computations also predicted a drag penalty at low-to-moderate lift coefficients.

Similar trailing-edge devices, such as the wedge flap and the divergent trailing edge, have been designed to increase airfoil efficiency at cruise conditions. The wedge flap[5] is a ramp located on the airfoil lower surface at the trailing edge with a height between 0.5–1.5% of the chord. At transonic velocities, the wedge flap lowers the angle of attack for a given lift coefficient and reduces the drag for lift coefficients above 0.52. Divergent trailing-edge (DTE) airfoils[6] have also shown significant improvement in transonic performance when applied to a supercritical airfoil. This modification incorporates strongly divergent upper and lower surfaces to produce a blunt trailing edge. Relative to a baseline supercritical airfoil, the DTE airfoil exhibits an increase in aft loading as well as a decrease in compressibility drag for a given lift coefficient.

Vortex generators have a long history of successful application to aerodynamic surfaces to prevent flow separation and increase efficiency. By generating streamwise vortices, these devices serve to energize the boundary layer which tends to delay the flow separation commonly encountered under adverse pressure gradients. First introduced by Taylor,[7] the vane-type vortex generators are the most ubiquitous, consisting of a flat plate mounted normal to the surface at a small angle of incidence to the local flow. Because they typically extend well beyond the boundary layer, this type of vortex generator produces considerable parasitic drag.[8] Submerged vortex generators, however, derive their name from the fact that they measure on the order of the boundary-layer thickness in height and are, therefore, mostly "submerged" in the boundary-layer flow. The submerged vortex generators investigated in this study were the Wheeler wishbone[9] type consisting of V-shaped ramps pointing in the downstream direction (Fig. 2). Each device generates two counter-rotating vortices, one off each edge, that grow with downstream distance.

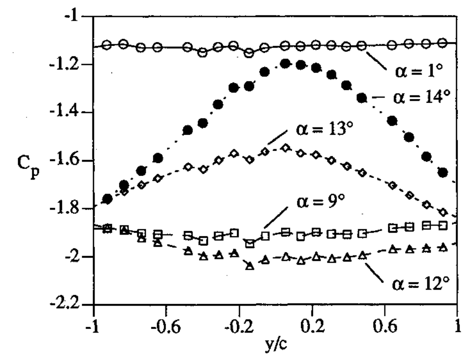

Fig. 4 Spanwise pressure coefficient variation at 0.25*c* for various angles of attack.

The primary objective of the present study was to provide an experimental data base on the performance of the Gurney flap on a single-element airfoil. Several flap sizes were tested in order to determine the effect of Gurney flap height and to validate the Navier-Stokes computations conducted previously by Jang et al.[4] A secondary objective was to determine the effectiveness of vortex generators in delaying airfoil stall.

Experimental Setup

The current experiment was conducted in the 7- by 10-ft Wind Tunnel at the NASA Ames Research Center. This facility is a closed-circuit wind tunnel incorporating a test section 15 ft long with a constant height of 7 ft and a width of 10 ft with a 1% divergence. There are no turbulence-reducing screens in the circuit and the test section turbulence intensity level is 0.77% at 100 ft/s. All data was obtained at a chord Reynolds number of approximately two million.

The model consisted of an NACA 4412 wing with a chord of 36 in. spanning the 10 ft width of the wind tunnel (Fig. 3). Boundary-layer trip strips were placed at 2.5 and 10% chord on the upper and lower surfaces, respectively. The airfoil was instrumented with a total of 200 pressure taps which composed one spanwise and three chordwise rows. The spanwise taps were located at one-quarter chord, while the chordwise rows were located at midspan and one-half chord on either side. The lift and pitching-moment coefficients were determined by an integration of the centerline pressure distribution, while the spanwise and additional chordwise rows of pressure taps served to monitor the two-dimensionality of the flow. In addition, boundary-layer fences were mounted on the airfoil 21 in. from each of the walls to promote two-dimensional flow on the instrumented center section.

The drag coefficient was determined by an integration of the static and total pressures measured with a wake rake situated 0.7 chord downstream of the airfoil trailing edge. The rake was composed of 91 total and 9 static pressure probes distributed over 36 in. with clustering near the centerline. A

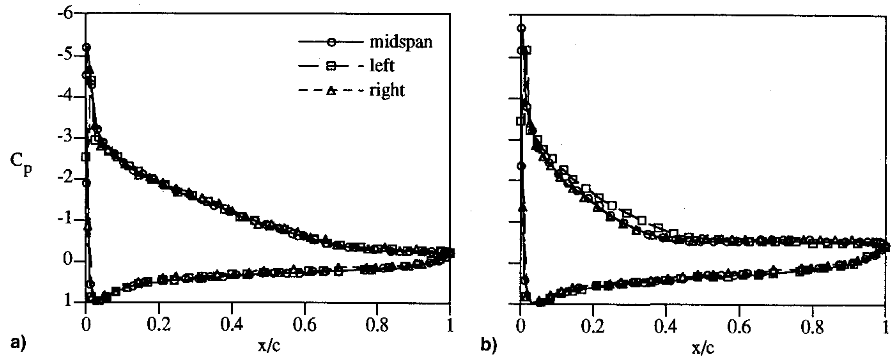

Fig. 5 Pressure distributions on the clean airfoil showing the character of the flow near and beyond $C_{l_{max}}$: a) α = 12 deg and b) α = 15 deg.

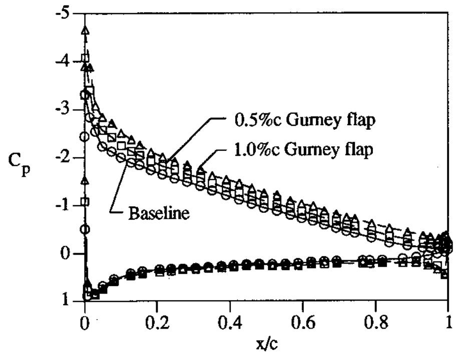

Fig. 6 Effect of Gurney flap height on chordwise pressure distribution at α = 9 deg.

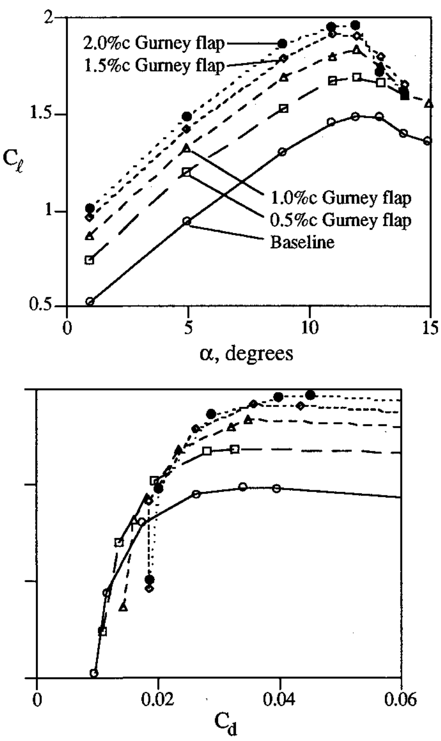

Fig. 7 Effect of Gurney flap height on the lift and drag coefficients.

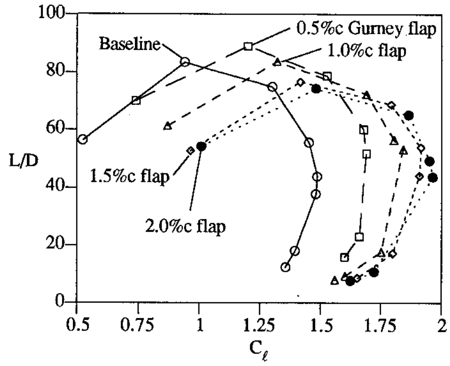

Fig. 8 Effect of Gurney flap height on lift-to-drag ratio.

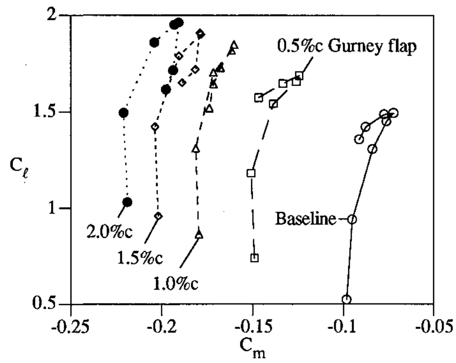

Fig. 9 Effect of Gurney flap height on pitching-moment coefficient.

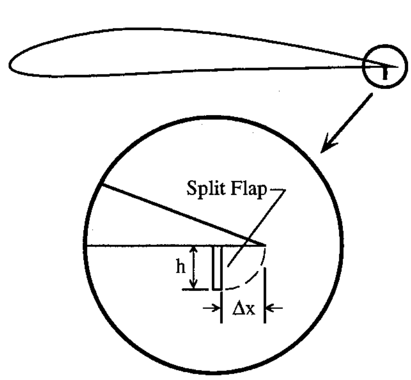

Fig. 10 Deployable miniature split-flap configuration.

motor-driven traverse was used to center the rake vertically on the airfoil wake at the midspan location. Both the wake rake pressures and surface pressures were measured with an electronically scanned pressure system for rapid data acquisition. All aerodynamic coefficients are reported in the wind axis system.

The two lift-enhancing devices were studied both independently and in concert. The effect of Gurney flap size was first investigated by testing flap heights of 0.5, 1.0, 1.5, and 2.0% chord. Wishbone vortex generators with a height of 0.5% chord were then tested with and without a Gurney flap. The vortex generators were mounted across the entire span at 12% chord from the leading edge, and were evenly spaced with a distance of six vortex generator heights between centers. At this location, their 0.5% chord height corresponds to approximately three to four boundary-layer thicknesses and they are, therefore, only partially submerged.

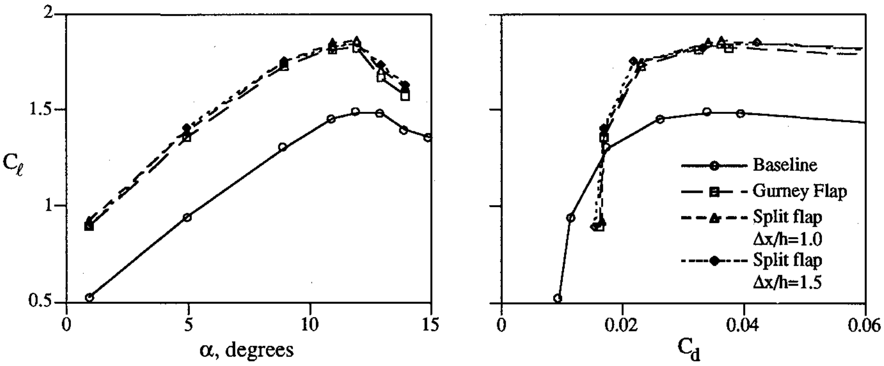

Fig. 11 Comparison of the Gurney flap and split flap configurations ($h = 1.25\%c$).

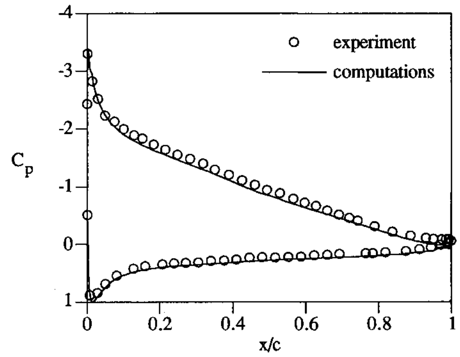

Fig. 12 Comparison of experimental and computed pressure distributions for the baseline airfoil at $\alpha = 9$ deg.

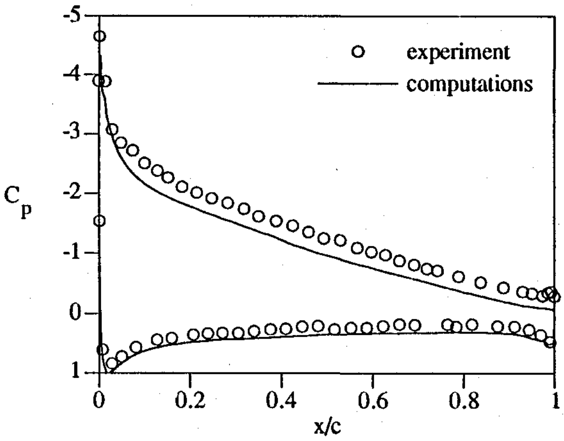

Fig. 13 Comparison of experimental and computed pressure distributions with a 1.0%c Gurney flap at $\alpha = 9$ deg.

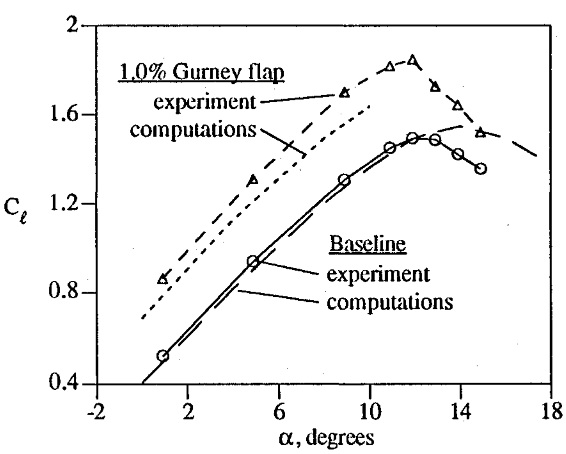

Fig. 14 Comparison of experimental and computed lift coefficient with and without a Gurney flap.

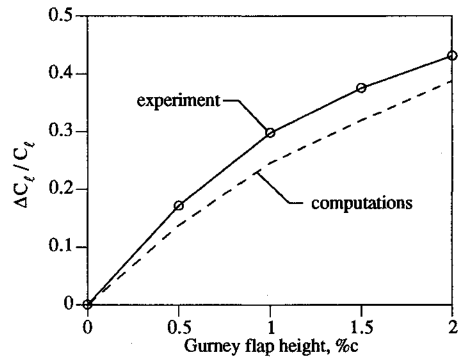

Fig. 15 Variation of lift coefficient increment with Gurney flap height.

Results and Discussion

The extent of two-dimensional flow is a good measure of the data quality in two-dimensional airfoil testing. The spanwise pressure variation for a representative case is presented in Fig. 4. These distributions indicate that the flow was essentially two-dimensional at the lower angles of attack, while some three-dimensionality is apparent near maximum lift ($\alpha = 12$ deg). At angles of incidence beyond maximum lift, however, strong three-dimensional effects are evident. These effects can also be observed in a comparison of the three chordwise pressure distributions (Fig. 5) where good correlation is observed at the maximum lift condition, while three-dimensional flow is indicated for the stalled condition.

Airfoil pressure distributions and wake surveys were first obtained for the baseline clean configuration and then for Gurney flap heights from 0.5 to 2% chord without vortex generators. A comparison of the pressure distributions for various Gurney flap heights is presented in Fig. 6. The presence of the Gurney flap considerably increased the aft loading of the airfoil, but it is also noted that much of the lift increment is derived from a general increase in loading and a higher suction peak. As the Gurney flap height is increased, higher loading is noted along the entire airfoil.

The lift and drag coefficients are presented in Fig. 7 for angles of attack from 0 to 15 deg. It can be seen that the addition of the Gurney flap produces a significant lift increment compared with the baseline configuration. The smallest Gurney flap tested (0.5%c) yielded an increase of 13% in the maximum lift coefficient, while the larger flaps produced successively larger increments, although not proportionally, up to 32% for the 2%c flap. Also shown in Fig. 8 is the drag polar for the same configurations. At low-to-moderate lift coefficients, there is a drag penalty associated with the Gurney flap which increases with flap height. At higher lift coefficients, however, the drag is significantly reduced. As a result, the effect on the maximum lift-to-drag ratio is small, but the lift coefficient for a given lift-to-drag ratio is significantly increased (Fig. 8). It is also noted that the maximum lift-to-drag ratio is reduced for Gurney flap heights greater than 1%

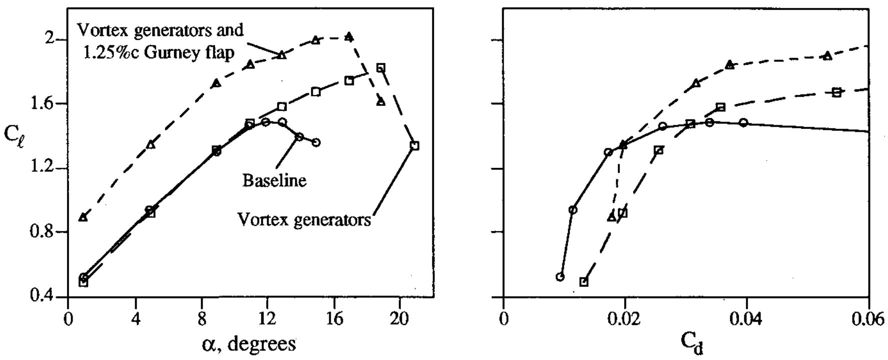

Fig. 16 Effect of vortex generators on the lift and drag coefficients with and without a Gurney flap.

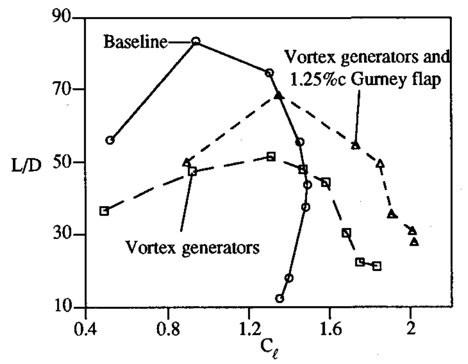

Fig. 17 Effect of vortex generators on the lift-to-drag ratio with and without a Gurney flap.

chord. Finally, the nose-down pitching moment about 0.25c (Fig. 9) is shown to increase with Gurney flap height although, again, not proportionally.

Because of the drag increment at lower lift coefficients caused by the Gurney flap, it would be desirable to stow the flap during cruise in aircraft applications. A sharp trailing edge, however, is not conducive to a hinge line and other hardware necessary for deployment. This prompted the consideration of a miniature split flap with a 90-deg deflection (Fig. 10). Two configurations were tested for a 1.25%c split flap with a hinge line located forward of the trailing edge by 1.0 and 1.5 flap heights, respectively. As illustrated in Fig. 11, these configurations yielded essentially the same results as the 1.25%c Gurney flap with no degradation in flap effectiveness.

The measured effect of the Gurney flap is in general agreement with the Navier-Stokes computations presented in Ref. 4. Figure 12 presents a comparison of the measured and calculated pressure distribution on the airfoil in the baseline clean configuration at an angle of attack of 9 deg. The lower pressures measured experimentally can be attributed to wall effects since the walls of the wind tunnel were not modeled in the computations. Larger discrepancies are evident in a similar comparison shown in Fig. 13 which incorporated a 1.0%c Gurney flap. Nevertheless, the computations effectively predicted the higher suction peak and the increased aft loading caused by the Gurney flap. A comparison of the computed and experimental lift coefficients for the baseline and 1%c Gurney flap cases is presented in Fig. 14. Good correlation is observed between computation and experiment for the baseline airfoil except near the maximum lift coefficient. The computations, however, appear to underpredict the lift increment due to the Gurney flap. This discrepancy was noted for each Gurney flap height tested. As illustrated in Fig. 15, the computed lift increment for flap heights between 0.5–2.0%c was consistently low compared with experiment.

Previous experimental and computational results[4,10] indicate that the NACA 4412 suffers a trailing-edge stall progression, a behavior especially suited for the application of vortex generators. The effect of the vortex generators was investigated both with and without a Gurney flap. As shown in Fig. 16, the addition of the vortex generators to the baseline configuration delayed the flow separation from an angle of attack of 12–19 deg, and increased the maximum lift coefficient by 23%. However, it is apparent from the drag polar that there is a significant drag penalty at low and moderate lift coefficients caused by the parasitic drag associated with the vortex generators. Figure 16 also presents the results from the synergism of the Wheeler vortex generators and a 1.25%c Gurney flap which yielded a 36% increase in the maximum lift coefficient at an angle of attack of 17 deg. The corresponding lift-to-drag ratio (Fig. 17) was significantly reduced for both configurations due to the large increase in drag. Thus, the resulting reduction in cruise performance greatly offsets the high-lift benefits obtained from these vortex generators. However, it has been proposed in Ref. 11 that vortex generators located near the leading edge of a flap could be stowed in the flap cove of the main element during cruise without a drag penalty. Similarly, these devices may be placed near the leading edge of the main element where they would be concealed by the slat in the cruise configuration.

Conclusions

Two lift-enhancing devices were experimentally investigated on a two-dimensional single-element airfoil and the following conclusions were drawn:

1) The Gurney flap can significantly increase the lift of a single-element airfoil with a small increase in drag at low-to-moderate lift coefficients.

2) To avoid a drag penalty during cruise, the miniature split flap configuration can be employed with a hinge line forward of the trailing edge, providing performance comparable with the Gurney flap.

3) Vortex generators can delay flow separation and increase the maximum lift coefficient on an airfoil that suffers trailing-edge stall. However, the large drag increment associated with these devices suggests that they must be incorporated into a high-lift system by placing them near the leading edge of the flaps and/or the main element where they will be concealed during cruise.

4) The Gurney flap and vortex generators can be employed in concert to generate greater lift enhancement than either device individually.

References

[1]Liebeck, R. H., "Design of Subsonic Airfoils for High Lift," *Journal of Aircraft*, Vol. 15, No. 9, 1978, pp. 547–561.

[2]Katz, J., and Largman, R., "Effect of 90 Degree Flap on the Aerodynamics of a Two-Element Airfoil," *Journal of Fluids Engineering*, Vol. 111, March 1989, pp. 93, 94.

[3]Katz, J., and Dykstra, L., "Study of an Open-Wheel Racing Car's Rear-Wing Aerodynamics," Society of Automotive Engineers International Congress and Exposition, SAE Paper 890600, Detroit, MI, Feb.–March 1989.

[4]Jang, C. S., Ross, J. C., and Cummings, R. M., "Computational Evaluation of an Airfoil with a Gurney Flap," *Proceedings of the 10th AIAA Applied Aerodynamics Conference* (Palo Alto, CA), AIAA, Washington, DC, 1992, pp. 801–809 (AIAA Paper 92-2708).

[5]Boyd, J. A., "Trailing Edge Device for an Airfoil," U.S. Patent 4542868, 1985.

[6]Gregg, R. D., Hoch, R. W., and Henne, P. A., "Application of Divergent Trailing-Edge Airfoil Technology to the Design of a Derivative Wing," Society of Automotive Engineers Aerospace Technology Conf. and Exposition, SAE Paper 892288, Anaheim, CA, Sept. 1989.

[7]Taylor, H. D., "The Elimination of Diffuser Separation by Vortex Generators," United Aircraft Corp., R-4012-3, East Hartford, CT, 1947.

[8]Rao, D. M., and Kariya, T. T., "Boundary-Layer Submerged Vortex Generators for Separation Control—An Exploratory Study," *Proceedings of the 1st National Fluid Dynamics Conference* (Cincinnati, OH), AIAA, Washington, DC, 1988, pp. 839–846 (AIAA Paper 88-3546).

[9]Wheeler, G. O., "Low Drag Vortex Generators," U.S. Patent 5058837, 1991.

[10]Wadcock, A. J., "Investigation of Low-Speed Turbulent Separated Flow Around Airfoils," NASA CR 177450, Aug. 1987.

[11]Lin, J. C., Robinson, S. K., McGhee, R. J., and Valarezo, W. O., "Separation Control on High Reynolds Number Multi-Element Airfoils," AIAA Paper 92-2636, June 1992.