Table 1 Comparison of core radius (r_c), with r_c defined in various ways

Flow conditions and model configuration	Measurement plane	r_c/c	$r_c/(b/2)$	Definition[a]
NACA 0015, $Re_c = 1.3 \times 10^5$, $\alpha = 14$ deg (present test)	$x/c = 10$ ($x/b \approx 1$)	0.09–0.13	0.02–0.03	[1]
Moore and Saffman[4] equation	$x/c = 10$	0.03	——	[3]
ONERA Peaky airfoil, 35-deg sweptback, $Re_c \approx 5 \times 10^5$ (Ref. 5)				
$\alpha = 11$ deg	$x/b = 0.35$	——	0.02	[2]
$\alpha = 12.8$ deg	$x/b = 0.35$	——	0.04	[2]
NACA 0015, $Re_c \approx 3 \times 10^5$ (Ref. 6)				
$\alpha = 8$ deg	$x/b = 10$	——	0.02	[1]?
$\alpha = 12$ deg	$x/b = 10$	——	0.02	[1]?
NACA 66-209, $Re_c = 6.83 \times 10^5$, $\alpha = 7.1$ deg (Ref. 7)	$x/c = 10$	——	0.03	[1]
NACA 0012, $Re_c = 5.3 \times 10^5$, $\alpha = 5$ deg (Ref. 8)	$x/c = 10$	——	0.05	[2]

[a][1] Positions of the two tangential velocity maxima; [2] edge of viscous wake, e.g., 1% total pressure loss contour; and [3] size of Rankine vortex.

of magnitude, though many of these earlier studies used point-measurement techniques without taking into account the effects of wandering, and made limited mention of the fluctuations (if any) in core sizes. In the present test, the extent of core movement, or wandering, has been found to be about 0.1c, which is comparable with the radius of the core itself. Knowing the time interval between data points, the velocity of wandering can also be estimated and found to be about 0.025–0.030 m/s, or roughly 4% of the freestream velocity.[1]

The cause of the unsteadiness is not certain, although it has often been attributed to the unsteadiness in the wind-tunnel freestream.[8] It may also be a result of flow separation over the airfoil, and may even be a genuine feature of any wing-tip vortex. In any case, the wandering motion is slow and could, in principle, be separated from other (turbulence) measurements using methods such as spectral decomposition[8] whenever a point-measurement technique is used. According to one particular study,[3] the measurement error in the peak tangential velocity can be as much as 35% if wandering effects are not included. As a global measurement technique, PIV therefore presents a definite advantage over point-measurement techniques such as hot wires and pressure probes.

Conclusions

Velocity measurements of wing-tip vortices have been obtained successfully in the IAR 9 m × 9 m Wind Tunnel using the PIV technique. At 14-deg AOA, the wing-tip vortices have been found to be highly unsteady, and the PIV technique has been shown to be an effective tool in obtaining instantaneous measurements of such unsteady flows. Further work is underway to refine its operation and extend its applicability under a wider range of flow conditions.

References

[1] Yeung, A. F. K., and Lee, B. H. K., "PIV Study of Wing Tip Vortices in the IAR 9 m × 9 m Wind Tunnel," *Proceedings of the Transport Canada International Wake Vortex Meeting* (Ottawa, Canada), 1997, pp. 91–93.

[2] Adrian, R. J., "Particle-Imaging Technique for Experimental Fluid Mechanics," *Annual Review of Fluid Mechanics*, Vol. 23, 1991, pp. 261–304.

[3] Baker, G. R., Barker, S. J., Bofah, K. K., and Saffman, P. G., "Laser Anemometer Measurements of Trailing Vortices in Water," *Journal of Fluid Mechanics*, Vol. 65, Pt. 2, 1974, pp. 325–336.

[4] Moore, D. W., and Saffman, P. G., "Axial Flow in Laminar Trailing Vortices," *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences*, Vol. 333, June 1973, pp. 491–508.

[5] El-Ramly, Z., and Rainbird, W. J., "Flow Survey of the Vortex Wake Behind Wings," *Journal of Aircraft*, Vol. 14, No. 1, 1977, pp. 1102–1108.

[6] Corsiglia, V. R., Schwind, R. G., and Chigier, N. A., "Rapid Scanning, Three-Dimensional Hot-Wire Anemometer Surveys of Wing Tip Vortices," *Journal of Aircraft*, Vol. 10, No. 12, 1973, pp. 752–757.

[7] Green, S. I., and Acosta, A. J., "Unsteady Flow in Trailing Vortices," *Journal of Fluid Mechanics*, Vol. 227, 1991, pp. 107–134.

[8] Devenport, W. J., Rife, M. C., Liapis, S. I., and Follin, G. J., "The Structure and Development of a Wing-Tip Vortex," *Journal of Fluid Mechanics*, Vol. 312, 1996, pp. 67–106.

Gurney Flap Experiments on Airfoil and Wings

C. P. van Dam* and D. T. Yen†
University of California, Davis,
Davis, California 95616
and
P. M. H. W. Vijgen‡
The Boeing Company, Seattle, Washington 98124-2207

Introduction

IN Ref. 1, Myose et al. present recent wind-tunnel results on the effects of Gurney flaps on the aerodynamic characteristics of several two- and three-dimensional lifting surfaces. The Gurney flap is a small vertical tab mounted at the trailing edge of a lifting surface normal to its pressure side. The idea behind this trailing-edge modification is to shift the location of the Kutta condition to enhance the lift generated by the lifting surface at given angle of attack. In Ref. 1, Myose et al. indicate that few results are available in the open literature on the effects of Gurney flaps for three-dimensional configurations. Their study includes lift and drag results for a wing with a natural laminar flow section shape and Gurney flaps of varying span. The purpose of this Note is to bring attention to a wind-tunnel study on the effects of Gurney-flap-like modifications for a three-dimensional wing with a similar section shape conducted ~10 years ago,[2] to compare the lift and aerodynamic efficiency (L/D) results obtained in this earlier test with those obtained in Ref. 1, and to point out possible aerodynamic advantages of three-dimensional modifications in the geometry of the Gurney flap.[3]

Received July 23, 1998; revision received Nov. 27, 1998; accepted for publication Dec. 7, 1998.

*Professor, Department of Mechanical and Aeronautical Engineering. Senior Member.

†Ph.D. Student, Department of Mechanical and Aeronautical Engineering.

‡Senior Specialist Engineer, Aerodynamics Engineering. Senior Member.

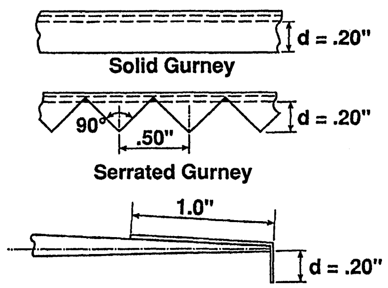

Fig. 1 Geometry and installation of solid and serrated Gurney flaps in experiment of Ref. 2.

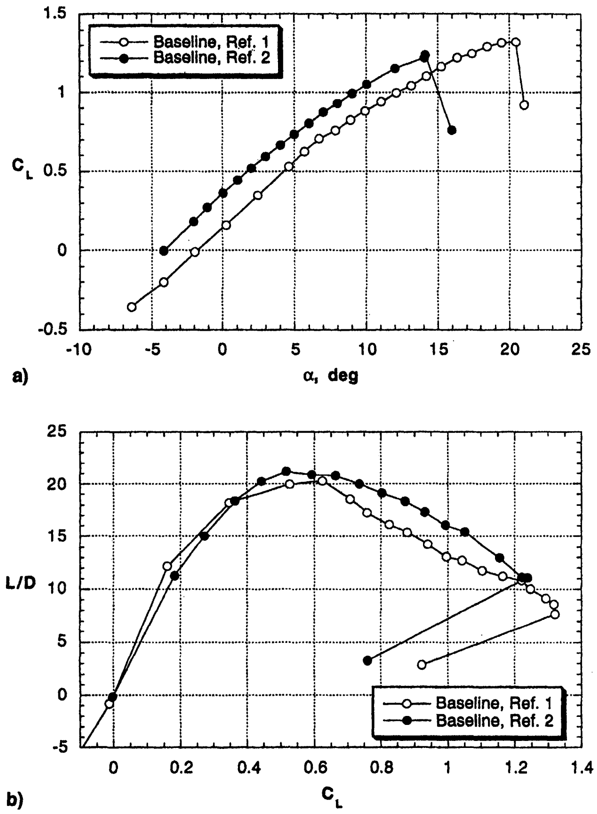

Fig. 2 Comparison of aerodynamic characteristics of baseline configurations: a) lift curves and b) *L/D* curves.

Analysis of Experiments

The wind-tunnel experiment of Ref. 1 was conducted in the Wichita State University Low-Speed Tunnel, which has a 7-ft high and 10-ft wide test section. The reflection-plane model consists of a constant chord (c = 1.25 ft) wing with a semispan of 5 ft and NLF(1)-0414F section shape.[4] The test was conducted at a Reynolds number of 1.2×10^6 with free transition. The most inboard station of the Gurney flaps is at y = 0.5 ft and flap spans of 1.5, 3.0, and 4.5 ft are analyzed. In Ref. 1, results are presented for Gurney flaps with a height of 0.033c. The wind-tunnel experiment of Ref. 2 was conducted in the 14- by 22-ft Subsonic Tunnel at NASA Langley Research Center. The wing–body model has a high-mounted tapered wing with NLF(1)-0414F section shape, a span of 12.81 ft, a reference chord c_{ref} (mean aerodynamic chord) of 1.10 ft, and a reference wing area of 13.06 ft^2. The body has a maximum width of 1.15 ft. The test was conducted at a Reynolds number of 1.1×10^6 with transition fixed at 0.05c on the upper and lower surface along the complete span. The Gurney flaps extend full span from $y = \pm 0.57$ ft to the tips for a total length of 5.8 ft per semispan. The flaps have a height of 0.20 in. or a nondimensional height based on c_{ref} of 0.015. In addition to the traditional (solid) Gurney flap, a modified flap as depicted in Fig. 1 was tested. This modified, or serrated, Gurney flap has the identical maximum height and span as the solid flap, but half the frontal area.

In Fig. 2, the lift and drag results of the two baseline configurations (without trailing-edge modifications) are compared. (The data presented in this Note are obtained by digitizing the data points in Figs. 5a and 5b of Ref. 1; Figs. 7a, 7b, and 7c of Ref. 2; and Fig. 4 of Ref. 5.) The NLF(1)-0414F airfoil in its basic configuration has a design lift coefficient of 0.4 (Ref. 4) and the baseline configuration of Ref. 2 is shown to generate this lift coefficient at zero angle of attack. The baseline configuration of Ref. 1 is shown to generate a lower lift coefficient at zero angle of attack, which may be the result of a slight modification in the design shape of the airfoil or of a different orientation of the angle-of-attack reference. The slopes of the two lift curves are nearly identical. The *L/D* curves of the two baseline configurations are very similar with both configurations generating $(L/D)_{max} \cong 21$ near $C_L = 0.5$. The agreement between the two sets of results is somewhat surprising given the differences in the planform geometries and the fact that transition is fixed in Ref. 2, whereas it is free in Ref. 1. The model used in Ref. 2 has a sizable centerbody, which reduces its effective aspect ratio. Also, transition is fixed near the leading edge in the experiment of Ref. 2, which negatively affects the overall aerodynamic efficiency. The agreement between the two sets of baseline results provides an excellent starting point to compare the effects of the trailing-edge modifications.

In Fig. 3, the effects of the Gurney-flap trailing-edge modifications on the aerodynamic characteristics of the two models are presented. In Fig. 3a, the lift results are plotted as a function of the angle of attack with respect to the zero-lift line

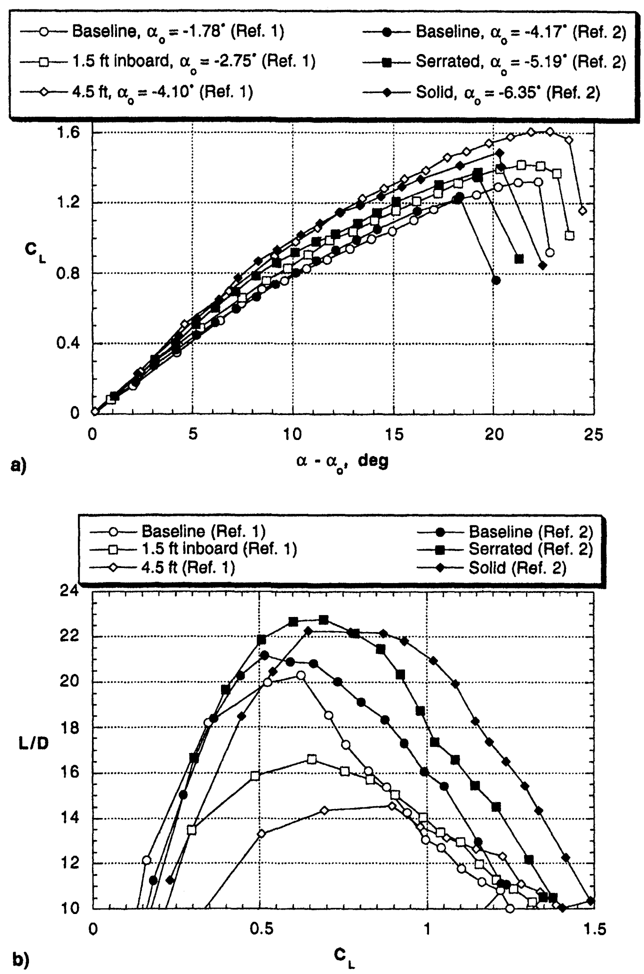

Fig. 3 Effect of Gurney-flap-type trailing-edge modifications on aerodynamic characteristics: a) lift and b) *L/D* curves.

facilitating comparison of the lift curves for the various configurations. Up to lift coefficients of approximately unity, the two sets of data in Fig. 3a are remarkably similar with the two baseline configurations as well as the two configurations with fully extended Gurney flaps (4.5 ft in Ref. 1 and solid in Ref. 2), depicting nearly identical lift-curve slopes. The values for the maximum lift coefficient are shown to differ; however, the maximum increment in $C_{L_{\max}}$ caused by the addition of the Gurney flap is, again, remarkably similar for both sets of data ($\Delta C_{L_{\max}} = 0.3$). Note that the shift in the zero-lift angle of attack α_0 from the baseline caused by the fully extended (4.5 ft) flap, is -2.32 deg in Ref. 1 whereas the shift from the baseline caused by the fully extended (solid) flap is slightly less at -2.18 deg in Ref. 2. There is a very noticeable steepening of the lift curve slope because of the trailing-edge modifications for angles of attack up to $\sim$10 deg. This steepening is the result of an apparent nonlinear change in effectiveness of the flap as a function of angle of attack, which is also observed in two-dimensional wind-tunnel experiments for the NLF(1)-0414F airfoil. In Fig. 4, the two-dimensional results by McGhee et al.[4] measured at a Reynolds number of 3.0×10^6 for a $0.0125c$ Gurney flap (reported in Ref. 5), and the three-dimensional results of Ref. 2 show a very similar change in α_0 and lift-curve slope. Hence, the steepening in the lift-curve slope caused by the trailing-edge modification appears to be two dimensional in nature.

In Fig. 3b, the effects of the trailing-edge modifications on the aerodynamic performance parameter, L/D, are presented. For both sets of data, the trailing-edge modifications result in a shift of C_L for $(L/D)_{\max}$ to higher lift coefficients. However, for the configurations of Ref. 1, $(L/D)_{\max}$ is shown to drop with increasing extent of the Gurney flap, whereas an increase in $(L/D)_{\max}$ is shown for the configurations of Ref. 2. This discrepancy is likely linked to 1) the effect of the trailing-edge modification on boundary-layer transition, which was kept free in Ref. 1 and fixed near the leading-edge in Ref. 2; and 2) the size of the Gurney flap that is $0.033c$ in Ref. 1 and $0.015c_{\mathrm{ref}}$ in Ref. 2. The Gurney flap changes the pressure distribution in such a manner that transition on the upper surface of the NLF(1)-0414F occurs naturally near the leading edge, even at low lift coefficients (see Figs. 4 and 5 of Ref. 5), resulting in a drag penalty for laminar-flow lifting surfaces. The larger flap size does little to further enhance the lift as demonstrated in Fig. 2a, but has a severely adverse effect on the drag. By comparison, note the beneficial effect of the serrated shape of the trailing-edge modification on the performance characteristics; L/D is better than the baseline wing for $C_L > 0.4$ and, unlike the solid flap, there is little or no L/D penalty at lower lift coefficients. The advantages of the serrated flap over the solid flap are as follows:

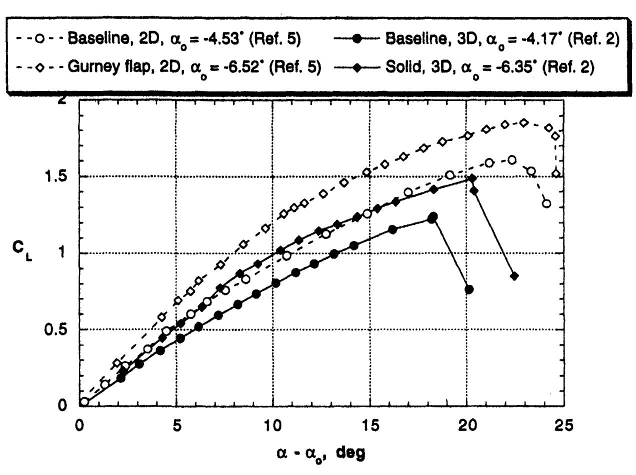

Fig. 4 Comparison of two-dimensional vs three-dimensional effect of Gurney-flap trailing-edge modification on lift of NLF(1)-0414F.

1) For a given lift increment, the spanwise load distribution, and hence, induced drag, may be less severely affected by a full-span serrated flap as compared with a part-span solid flap.

2) The streamwise vorticity created by the serrations may reduce or eliminate flow separation in the trailing-edge region as explained in more detail in Ref. 2.

Finally, Ref. 2 presents the effects of Gurney-flap additions on nose-down pitching moment (not shown in Ref. 1), requiring the consideration of trim-drag implications.

Concluding Remarks

The results of Refs. 1 and 2, both at a Reynolds number of approximately 1×10^6, are largely in agreement in terms of the overall effect of Gurney flaps on the lift characteristics of wings. However, the larger solid flaps tested in Ref. 1 provide little additional lift benefit while negatively affecting the drag. In comparison, the $0.015c_{\mathrm{ref}}$ Gurneys in Ref. 2 allow an increase in $(L/D)_{\max}$ of $\sim$6%. Maybe the most important observation is that continuous Gurney flaps are not required to be effective on three-dimensional configurations. As shown, spanwise variations in the flap geometry, such as serrations, allow modulation of the lift increment without accruing (severe) drag penalties.

References

[1]Myose, R., Papadakis, M., and Heron, I., "Gurney Flap Experiments on Airfoils, Wings, and Reflection Plane Model," *Journal of Aircraft*, Vol. 35, No. 2, 1998, pp. 206–211.

[2]Vijgen, P. M. H. W., van Dam, C. P., Holmes, B. J., and Howard, F. G., "Wind-Tunnel Investigations of Wings with Serrated Sharp Trailing Edges," *Low Reynolds Number Aerodynamics*, edited by T. J. Mueller, Vol. 54, Lecture Notes in Engineering, Springer–Verlag, New York, 1989, pp. 295–313.

[3]Vijgen, P. M. H. W., Howard, F. G., Bushnell, D. M., and Holmes, B. J., "Serrated Trailing Edges for Improving Lift and Drag Characteristics of Lifting Surfaces," US Patent 5,088,665, Feb. 18, 1992 (Invention Disclosure LAR 13870-1-CU, Aug. 31, 1987).

[4]McGhee, R. J., Viken, J. K., Pfenninger, W., Beasley, W. D., and Harvey, W. D., "Experimental Results for a Flapped Natural-Laminar-Flow Airfoil with High Lift/Drag Ratio," NASA TM 85788, May 1984.

[5]Neuhart, D. H., and Pendergraft, O. C., Jr., "A Water Tunnel Study of Gurney Flaps," NASA TM 4071, Nov. 1988.

Flowfield Simulation About a 65-Degree Delta Wing During Constant Roll-Rate Motions

Jeffrey C. Tromp*

U.S. Air Force Research Laboratory, Wright–Patterson Air Force Base, Ohio 45433-7521

Introduction

THE effects of roll and yaw rates on aerodynamic reactions and vortex breakdown locations for a 65-deg delta wing are described. Two distinct maneuvers are numerically simulated to isolate the rate effects. The first is a constant-rate coning motion, with computed body-axis moments compared with

Presented as Paper 98-4453 at the AIAA Atmospheric Flight Mechanics Conference, Boston, MA, Aug. 10–12, 1998; received Oct. 21, 1998; accepted for publication Nov. 3, 1998.

*Aerospace Engineer, AFRL/VAAC, Building 146, 2210 Eighth Street, Suite 11. Senior Member AIAA.