JOURNAL OF AIRCRAFT
Vol. 48, No. 1, January–February 2011

Engineering Notes

Effect of Streamwise Attachment Gap on Aerodynamic Characteristics of Gurney Flaps

Lance W. Traub* and Eric O. Freienmuth†
Embry-Riddle Aeronautical University, Prescott, Arizona 86301

DOI: 10.2514/1.C031226

Introduction

THE simplicity and effectiveness of the Gurney flap, a thin plate typically attached perpendicular to the pressure side of an airfoil, has resulted in a concerted and sustained research effort to characterize the Gurney flap's behavior [1–5]. Because of suction induced by an asymmetric von Karman vortex street shed from the flap [1] and lower surface flow compression upstream of the flap, the Gurney creates a finite pressure difference at the trailing edge. Final pressure recovery occurs in the wake. The flaps have been observed to generate significant lift augmentation, with the magnitude scaling with the square root of the flap length [5]. For flaps within the boundary-layer thickness, lift augmentation may not be accompanied by a drag penalty. The characterization of these flaps has encompassed the effect of their inclination angle [2,6], porosity [7], chordwise attachment location on the airfoil [2], and geometry [8]. However, the effect of location of the flap, if downstream of the trailing edge, has received little attention. Consequently, this study aims to elucidate the aerodynamic behavior of Gurney attachment aft of the trailing edge and whether such locations have any potential benefit. Thus, a low-speed wind-tunnel investigation was undertaken, using a platform balance while wake-shedding characteristics were established using a hot-wire anemometer.

Equipment and Procedure

Wind-tunnel tests were conducted in Embry-Riddle University's 1×1 ft. open return facility. This wind tunnel has a measured turbulence intensity of 0.5% and jet uniformity within 1% in the core. The wall boundary layer is approximately 5 mm thick. Force measurements were recorded using an in-house, designed and manufactured low-range platform balance. The balance has a maximum range of 43 N and a demonstrated accuracy, resolution, and repeatability of 0.0098 N. Angle setting ability is within 0.1 deg. Tests were conducted at a Reynolds number of 150,000, corresponding to a freestream velocity of 27 m/s, with an air density of 1 $\mathrm{kg/m^3}$. A computer-controlled acquisition system was written for this balance using LabView 8.2. Repeated force balance data measurements in the attached flow regime (4 deg incidence) and at stall (14 deg incidence) yielded an uncertainty for the lift and drag coefficients of 0.014 and 0.001, and 0.02 and 0.01, for a 95.5% probability, respectively.

A wing was designed for force balance testing using the computer-aided three-dimensional interactive application (CATIA) software, and then it was rapid prototyped using Embry-Riddle's rapid prototyping facilities, yielding an acrylonitrile butadiene styrene plastic wing representation. The wing chord c was 100 mm. The wing section was a S8036. The profile was chosen due to its effective performance at low Re and comparatively thick trailing-edge region (allowing flap attachment). The wing spanned the tunnel with a gap of less than 0.5 mm at each end; thus, the data may be considered sectional or that for the airfoil. At the test Re of 150,000, this airfoil has been shown to exhibit a large upper surface laminar separation bubble, which contracts and moves forward with incidence [9]. The Gurney flaps were made from thin (0.79 mm) aluminum plate. The plate was attached to four thin rods, which in turn could slide into the wing to facilitate gap setting. Gurney flap lengths of 2 mm (2% flap length), 4 mm (4% flap length), and 6 mm (6% flap length) were evaluated. Gaps between the trailing edge and the front of the flap of 0 mm ($\mathrm{gap}/c = 0$), 1 mm ($\mathrm{gap}/c = 0.01$), 2 mm ($\mathrm{gap}/c = 0.02$), 4 mm ($\mathrm{gap}/c = 0.04$), and 6 mm ($\mathrm{gap}/c = 0.06$) were implemented. Shedding characteristics behind the flap were established using TSI's IFA 300 constant temperature hot-wire anemometer. Data were digitized using a 14-bit National Instruments A/D board. A LabView 8.2 data acquisition code was written to provide real-time spectral analysis of the temporal data. Because of the comparative nature of the tests, wall corrections were not applied. Forced transition was not employed in any of the tests (i.e., trip strips were not used).

Results and Discussion

At a low Re number, data fidelity is a major concern due to the low magnitude of the imposed loads. Consequently, Fig. 1 presents a repeated data run for the clean wing, i.e., without the flap attached. As may be seen, repeatability in the primarily attached flow regime is very good. Of interest is the significant variance in the stall characteristics and hysteretic behavior, even though the two tests were performed in succession. The variation in the lift curve slope initiated at approximately 3 deg incidence is commonly associated with the movement of the laminar transitional bubble over the upper surface. At low incidence, the bubble is located aft and is a significant extent of the chord (20–30%). This has the effect of decambering the airfoil through displacement thickness effects. Increasing incidence sees the bubble moving forward, attenuating the decambering, indicated as an apparent lift curve slope increase in Fig. 1. Inset in Fig. 1 is a surface skin friction image from [9] acquired over a similar airfoil at 4 deg incidence. The bubble is seen to have moved to the midchord location.

Figures 2a and 2b present a summary of the lift and drag coefficient behavior as affected by gap. As may be seen in Fig. 2a, the flap gap has a relatively minor impact on the hysteretic behavior. Increasing the flap gap reduces lift for a given incidence for all flap lengths (Fig. 2a). The initial movement of the flap downstream shows the largest relative loss of lift (i.e., compare 1 to 0% gap). It may be observed that the net effect of gap is analogous to decambering, displacing the lift curve down without a significant change in lift curve slope. However (excluding the 6% long flap), the stall angle is unaffected, a commonly seen result for Gurney flaps, as the device provides relief of the adverse pressure gradient near the trailing edge affected through an increase in upper surface dumping velocity. The loss of lift with gap is due to reduced lower surface compression; the pressure side flow is no longer trapped upstream of the flap as well as reduced suction from the increased proximity of the flap's vortex

Received 3 September 2010; revision received 25 October 2010; accepted for publication 27 October 2010.

*Associate Professor, Aerospace and Mechanical Engineering Department. Member AIAA.
†Undergraduate Student, Aerospace and Mechanical Engineering Department.

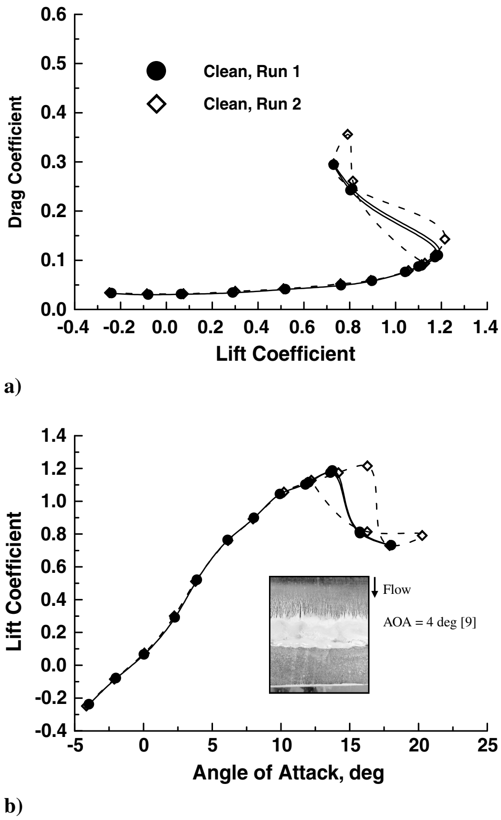

Fig. 1 Repeated data runs.

street from the suction surface. Both effects would tend to attenuate the finite pressure difference across the trailing edge. An interesting observation is that if the flap gap is greater than or equal to the flap's length, the lift plot shows a discontinuity (see arrows on plot) similar to that seen on the clean wing and usually associated with the movement of the laminar separation bubble. This may be a consequence of the Gurney flap effect diminishing, such that the increase in the leading-edge suction peak relative to the clean airfoil is not realized (and, as a result, the separation bubble is not fixed in place). It may be seen (Fig. 2a) that geometries that show marked lift augmentation compared with the clean airfoil generally do not have the kinks at approximately 3 and 6 deg incidences, as indicated by arrows 1 and 2. This may be due to the higher suction peak (and thus initial pressure recovery demands: higher adverse pressure gradient causing separation) common to Gurney flaps essentially fixing the bubble location at moderate to high incidence. Consequently, there appears to be a critical gap/flap length ratio of 1:1 above which lift augmentation is lost. The discontinuity at arrow 1, as mentioned, is due to the forward movement of the separation bubble. Arrow 2 (Fig. 2a) is indicative of the onset of turbulent trailing-edge flow separation, which is shown by arrow 2 (same data point as in Fig. 2a) in Fig. 2b, and coincides with a significant drag rise. Although all configurations may have a forward bubble location for an incidence of 5 deg or greater, not all configurations show the second stall initiated discontinuity, as indicated by arrow 2. Those that do not (i.e., flaps that still show significant lift augmentation compared with the clean wing despite the gap: 0 to 2% gap for the 4% flap and all 6% flaps, excluding a 6% gap) still benefit from the trailing-edge pressure recovery relief induced by the flap. With respect to drag, increasing the flap gap leads to a systematic increase in the minimum-drag coefficient. It appears that Gurney flap addition leads to a flatter drag polar (less curvature in the attached regime), indicative of less pressure drag. This ties in with reduced pressure recovery demands

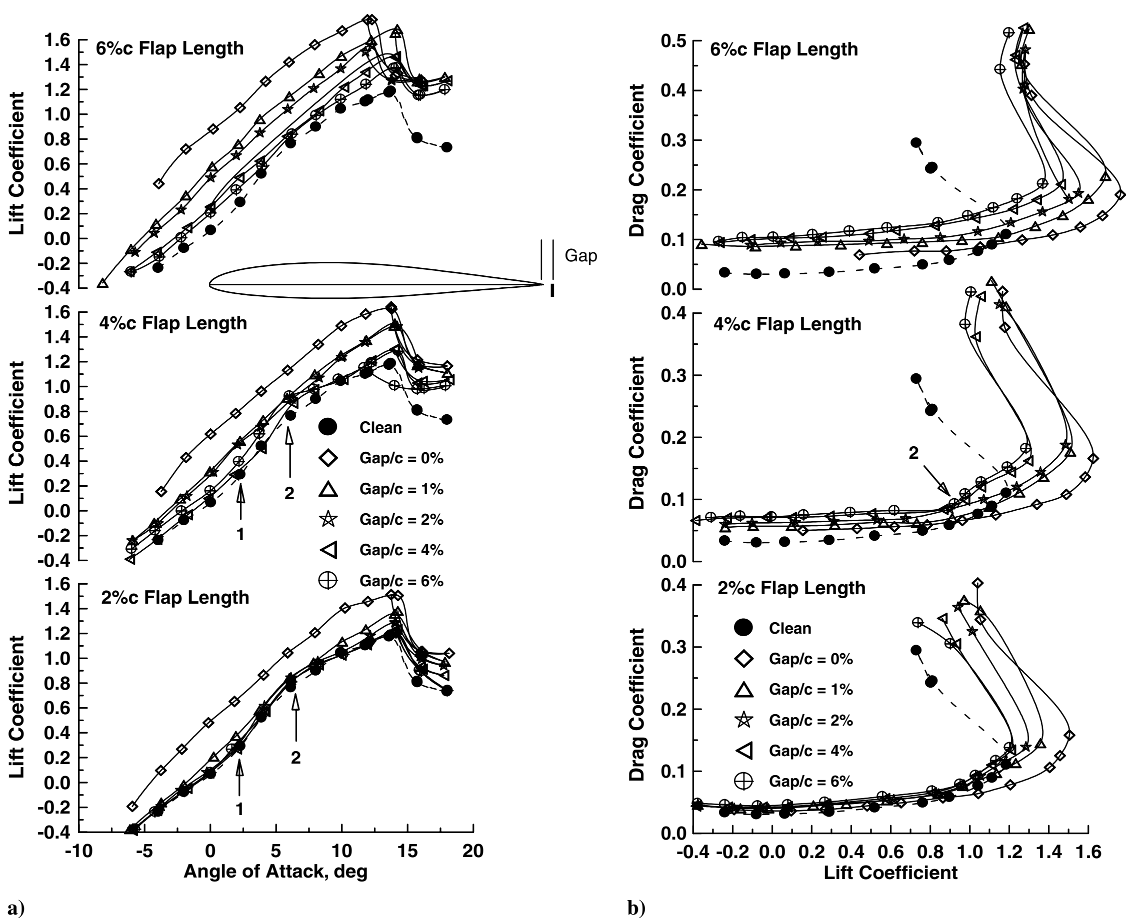

Fig. 2 Effect of Gurney flap gap on a) lift and b) drag coefficients.

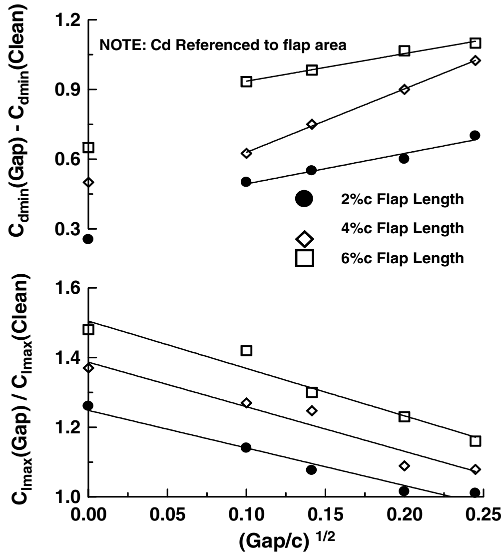

Fig. 3 Longitudinal force coefficient gap dependency.

toward the airfoil's trailing edge yielding a thinner upper surface boundary layer, and thus displacement thickness.

Figure 3 shows a data summary indicating the impact of flap gap explicitly on the normalized maximum lift coefficient $C_{l\max}$ and the minimum-drag coefficient $C_{d\min}$. The data are presented as a function of the square root of the gap/c. Both theoretical and experimental studies have indicated that flap aerodynamic impact scales with the square root of the flap height [4,5]; consequently, this dependency is also examined for gap. As shown, within the range tested, increasing gap results in a systematic reduction in the maximum lift coefficient achieved. The lift increments presented also appear to scale somewhat linearly with the flap length (i.e., the vertical spacing between the lines is similar). As depicted, the normalized maximum lift coefficient does indeed show a linear variation with $(\text{gap}/c)^{1/2}$ for all presented data. To explore the pressure drag acting on the flap, the measured minimum-drag difference between the clean airfoil and that with flap was nondimensionalized by the flap area and the freestream (assuming that the drag difference at the minimum-drag condition is primarily due to pressure loading across the flap). For an isolated two-dimensional plate, the drag coefficient commonly cited in the literature is approximately two [10]. As seen, the values presented are far lower and may be a result of the plate being imbedded in an effective freestream that is below that of the far-field freestream. The incremental minimum-drag coefficient shows a strong correlation with $(\text{gap}/c)^{1/2}$ but only for gaps greater than 0.01. Note that the initial displacement of the flap to 1% of the chord downstream shows a considerably larger drag increment than subsequent equal distance displacements.

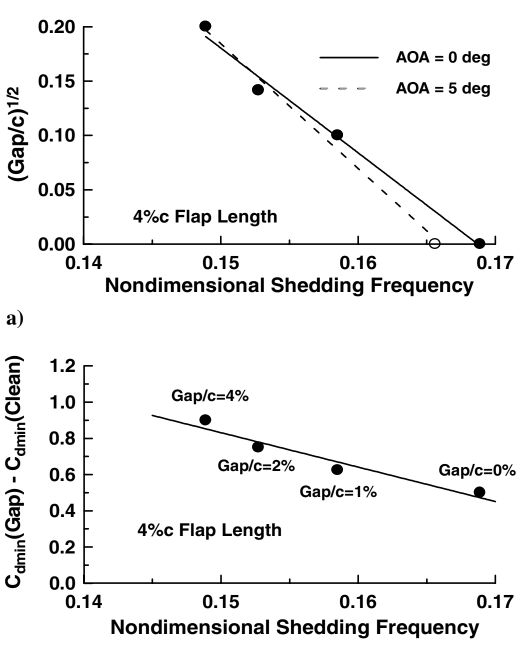

Fig. 4 Dependency of a) gap and b) minimum drag on flap shedding frequency (AOA denotes angle of attack).

Figure 4 presents a summary of spectral data recovered from measurements taken downstream of the flap using a hot-wire anemometer. Twenty power spectra were ensemble-averaged to define dominant frequencies, which are presented as a nondimensional frequency (i.e., Strouhal number: the shedding frequency multiplied by the flap length and reduced by the freestream velocity). Troolin et al. [11] recorded Strouhal numbers for a similar flap of 0.205 and 0.19 at 0 and 5 deg incidences, respectively. The shedding frequency was seen to show a weak linear reduction with incidence. The reduction in shedding frequency with incidence was suggested to be a result of increasing distance between the shear layers (due to upper surface boundary-layer thickening) that forms the alternating vortex street. The present data indicate Strouhal numbers of 0.168 and 0.166 for 0 and 5 deg incidences. As shown in Fig. 4a, the shedding frequency shows a systematic reduction as the flap is displaced streamwise (increasing gap), with a linear dependency on $(\text{gap}/c)^{1/2}$ shown. The shedding frequency drops from 0.168 (1140 Hz) to 0.149 (1005 Hz) as the gap varies from 0 to 6%c $[(\text{gap}/c)^{1/2} = 0.2]$. For the limited incidence range presented, angle of attack does not appear to affect the shedding frequency when the flap is aft of the trailing edge.

The reduction in shedding frequency with streamwise flap displacement may be due to an expansion of the wake flow around the flap, as it behaves essentially as a downstream obstacle (Fig. 4a). This would increase the spacing of the shear layers emanating from the flap edges, reducing the shedding frequency (the shedding process is dependent on a shear layer mutual induction effect to terminate lengths of the shear layer so as to roll up, forming coherent vortical structures). A greater shear layer separation requires a longer physical time for one shear layer to cross the median line of the flap and sever the opposing layer from its feeding sheet. In addition, the Gurney flap, when displaced aft of the trailing edge, may be situated in a local wake-type freestream, which would cause a reduction in shedding frequency. The relationship of the drag increment (between the 4% flap and the clean wing at 0 deg incidence) to the flap shedding frequency is explored in Fig. 4b. The greatest reduction in shedding frequency is seen to be associated with the initial displacement of the flap from the trailing edge (gap/$c = 0\%$) to 1% aft (gap/$c = 1\%$). Increasing gap shows a linear relation between the minimum-drag coefficient and shedding frequency. The linear increase in the minimum-drag coefficient increment, which is primarily due to increased bluffbody drag from the Gurney plate (that in turn relates to the wake width, which governs the shedding frequency), suggests an increase in wake width with gap for the gap range explored. Note that the discontinuity in the drag coefficient increment for the initial flap displacement (Fig. 3, top plot) and subsequent flap movement are not apparently reflected in a similar discontinuity in shedding frequency.

Conclusions

A low-speed wind-tunnel investigation was undertaken to characterize the impact of a streamwise displacement of a Gurney flap aft of an airfoil's trailing edge. Testing was undertaken at $Re = 150{,}000$ using a S8036 sectioned wing. Loads were established using a low-range platform balance, while flap shedding behavior was examined using hot-wire anemometry. Flap lengths of 2, 4, and 6% of the airfoil's chord were tested, while gaps of 1, 2, 4, and 6% were examined. The data showed that lift reduced and the minimum-drag coefficient increased proportionally to the square root of the gap length. The nature of the lift reduction was analogous to camber with a downward curve shift. The initial downstream displacement of the flap showed a larger loss of lift and increase of drag than subsequent equal-distance displacements. The shedding frequency of the vortex street aft of the flap also showed a reduction proportional to the square root of the gap length. As the net impact of the gap is deleterious to performance, this study suggests that any longitudinal gap between the airfoil and flap should be avoided.

Acknowledgments

The authors would like to thank the Associate Editor and reviewer for their helpful comments and suggestions.

References

[1] Jeffrey, D. R., and Hurst, D., "Aerodynamics of the Gurney Flap," AIAA Paper 1996-2418, 1996.

[2] Li, Y., Wang, J., and Zhang, P., "Influences of Mounting Angles and Locations on the Effects of Gurney Flaps," *Journal of Aircraft*, Vol. 40, No. 3, 2003, pp. 494–498. doi:10.2514/2.3144

[3] Maughmer, M. D., and Bramesfeld, G., "Experimental Investigation of Gurney Flaps," *Journal of Aircraft*, Vol. 45, No. 6, 2008, pp. 2062–2067. doi:10.2514/1.37050

[4] Traub, L. W., "Effects of Gurney Flaps on an Annular Wing," *Journal of Aircraft*, Vol. 46, No. 3, 2009, pp. 1085–1088. doi:10.2514/1.43096

[5] Liu, T., and Montefort, J., "Thin-Airfoil Theoretical Interpretation for Gurney Flap Lift Enhancement," *Journal of Aircraft*, Vol. 44, No. 2, 2007, pp. 667–671. doi:10.2514/1.27680

[6] Traub, L. W., Miller, A. C., and Rediniotis, O., "Preliminary Parametric Study of Gurney Flap Dependencies," *Journal of Aircraft*, Vol. 43, No. 4, 2006, pp. 1242–1244. doi:10.2514/1.13852

[7] Lee, T., "Aerodynamic Characteristics of Airfoil with Perforated Gurney Type Flaps," *Journal of Aircraft*, Vol. 46, No. 2, 2009, pp. 542–548. doi:10.2514/1.38474

[8] Meyer, R., Hage, W., Bechert, D. W., Schatz, M., and Thiele, F., "Drag Reduction on Gurney Flaps by Three Dimensional Modifications," *Journal of Aircraft*, Vol. 43, No. 1, 2006, pp. 132–140. doi:10.2514/1.14294

[9] Traub, L. W., and Cooper, E., "Experimental Investigation of Pressure Measurement and Airfoil Characteristics at Low Reynolds Numbers," *Journal of Aircraft*, Vol. 45, No. 4, 2008, pp. 1322–1333. doi:10.2514/1.34769

[10] Talay, T. A., "Introduction to the Aerodynamics of Flight," NASA SP 367, 1975.

[11] Troolin, D. R., Lai, W. T., and Longmire, E. K., "Time Resolved PIV Analysis of Flow Over a NACA 0015 Airfoil with Gurney Flap," *Experiments in Fluids*, Vol. 41, No. 2, 2006, pp. 241–254. doi:10.1007/s00348-006-0143-8