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Gurney Flap Experiments on Airfoils, Wings, and Reflection Plane Model

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The effect of Gurney flaps on two-dimensional airfoils, three-dimensional wings, and a reflection plane model were investigated. There have been a number of studies on Gurney flaps in recent years, but these studies have been limited to two-dimensional airfoil sections. A comprehensive investigation on the effect of Gurney flaps for a wide range of configurations and test conditions was conducted at Wichita State University. A symmetric NACA 0011 and a cambered GA(W)-2 airfoil were used during the single-element airfoil part of this investigation. The GA(W)-2 airfoil was also used during the two-element airfoil study with a 25% chord slotted flap deflected at 10, 20, and 30 deg. Straight and tapered reflection plane wings with natural laminar flow (NLF) airfoil sections were tested for the three-dimensional wing part of this investigation. A fuselage and engine were attached to the tapered NLF wing for the reflection plane model investigation. In all cases the Gurney flap improved the maximum lift coefficient compared to the baseline clean configuration. However, there was a drag penalty associated with this lift increase.

Nomenclature

C_d = drag coefficient
C_l = lift coefficient
C_m = pitching moment coefficient, quarter- or half-chord as indicated
c = chord length
q = freestream dynamic pressure, $\frac{1}{2}\rho U_\infty^2$
U_∞ = freestream velocity
x, y, z = streamwise, spanwise, and normal directions
α = angle of attack
δ = flap deflection
ρ = freestream density

Introduction

THE Gurney flap is a short flat plate attached to the trailing edge perpendicular to the chordline on the pressure side of an airfoil. Race-car driver Dan Gurney used this flap to increase the down force and, thus, the traction generated by the inverted wings on his race cars. Field tests by Gurney found that the flap increased the lift, i.e., traction, while the drag was slightly decreased.[1] Increasing the Gurney flap height beyond 2% of chord continued to increase the lift, but at the cost of substantially increased drag.

Numerous wind-tunnel tests on Gurney flaps have been conducted on both single and multielement airfoils (see Giguère et al.[2] for an extensive list). Liebeck[1] found that the lift was increased when a Gurney flap was attached to a Newman airfoil. Tuft flow visualization during the experiment indicated a downward turning of the flow behind the Gurney flap. Dye flow visualization on a NACA 0012 airfoil by Neuhart and Pendergraft[3] also showed a downward turning of the flow behind the Gurney flap. Airfoil pressure distribution measurements were taken on an advanced technology airfoil.[3] It was found that the Gurney flap produced an overall decrease in pressure on the upper surface and an overall increase in pressure on the lower surface as compared to the clean airfoil. This increase in the airfoil's circulation is presumably associated with the downward turning of the flow behind the airfoil. Storms and Jang[4] measured aerodynamic loads and pressure distributions on a NACA 4412 airfoil. They found that the Gurney flap generated an additional nose-down pitching moment compared to the clean airfoil. Myose et al.[5] measured aerodynamic loads, airfoil pressure distributions, wake, and boundary-layer profiles for a NACA 0011 airfoil with Gurney flaps. They found that the wake behind the airfoil was shifted downward, as suggested by the earlier flow visualization studies.

Previous studies,[1–5] which include aerodynamic load results, show that the Gurney flap increases the maximum lift coefficient, decreases the angle of attack of zero lift while the lift curve slope remains relatively constant, and increases the nose-down pitching moment. All of these results indicate that the Gurney flap increases the effective camber of the airfoil. A computational study by Jang et al.[6] further suggests that the Gurney flap works by affecting the Kutta condition on the airfoil. The downward turning of the flow relieves the adverse pressure gradient near the trailing edge and, thus, increases the suction over the upper surface. Giguère et al.[2] suggest that the increase in lift with the Gurney flap is obtained with very little penalty in drag because the Gurney flap resides within the airfoil's boundary layer. Based on their results[3] (on LA 203 and Göttingen 797 airfoils) as well as a review of past studies, they found that the maximum lift-to-drag ratio could be obtained when the Gurney flap height was equal to the boundary-layer thickness.

On two-element airfoils, a Gurney flap can be placed on the trailing element alone,[7–9] or on the main element alone,[8–10] or on both elements.[8,9,11] When the Gurney flap was located on the trailing element, an increase in lift was obtained.[7–9,11] A Gurney flap on the main element did not significantly improve the lift performance when the gap width between the main and trailing elements was narrow.[8,9,11]

As indicated by the previously mentioned literature survey, there have been a number of studies on the effect of Gurney flaps. However, these studies have been limited in terms of configuration, i.e., two-dimensional airfoils, and oftentimes in terms of measurement types, e.g., aerodynamic loads and air-

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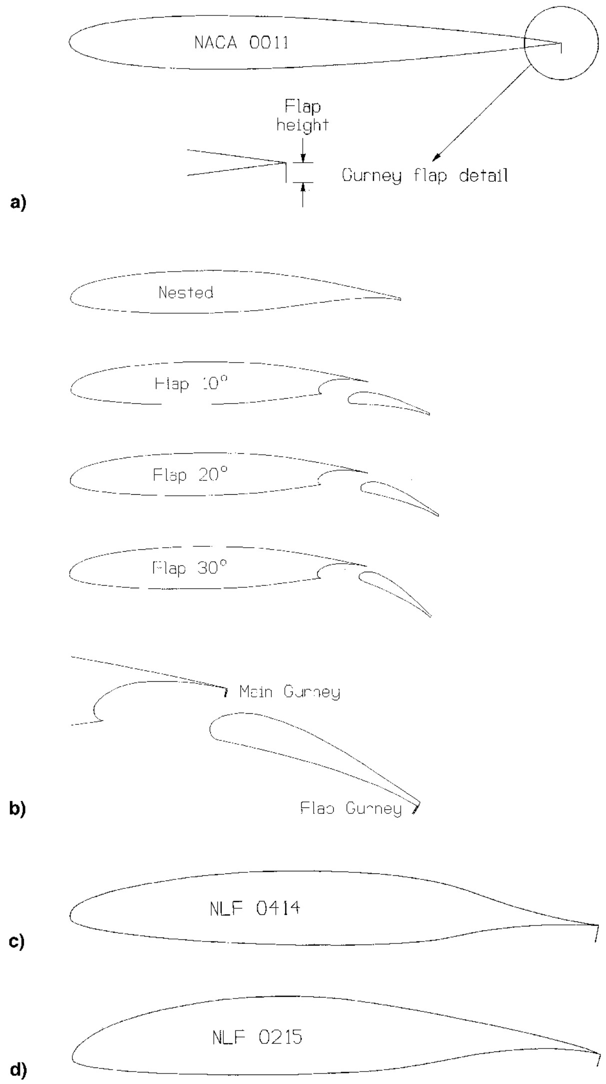

Fig. 1 Airfoil and wing profiles: a) NACA 0011 airfoil, b) GA(W)-2 airfoil, c) NLF 0414 profile, and d) NLF 0215 profile.

foil pressure distribution. Thus, the objective of the research effort at Wichita State University has been to conduct a comprehensive study on Gurney flaps for a wide range of configurations, test conditions, and measurement types. Thus far, Gurney flaps of varying heights have been tested on two-dimensional airfoils [NACA 0011 (Refs. 5 and 12) and GA(W)-2 (Refs. 8 and 9)], three-dimensional reflection plane wings [natural laminar flow (NLF), Ref. 13, and NACA 6-series], and a twin engine reflection plane model (Ref. 14). The purpose of this paper is to summarize the aerodynamic load results from these numerous investigations at Wichita State University.

Experimental Setup

The experiment was conducted in the Wichita State University Beech Memorial low-speed wind tunnel. This closed-return-type wind tunnel consists of four screens for flow conditioning, a 6:1 ratio contraction section, and a 7-ft high by 10-ft wide by 12-ft long test section. The maximum speed of the Beech wind tunnel is 160 mph (235 ft/s) corresponding to a Reynolds number of 1.5×10^6/ft. The facility is equipped with a truncated pyramid-type external balance that is capable of measuring up to six components of aerodynamic force and moment data simultaneously. Because the present experiment consisted of tests on two-dimensional airfoils and reflection plane, i.e., semispan, wing models, only the lift, drag, and pitching moment were measured by the balance. The resolution of the pyramid balance is 0.20 lb in lift, 0.05 lb in drag, and 2 in.-lb in pitching moment. Additional details about the balance are presented in Ref. 15. To eliminate the effects of boundary-layer buildup along the wind-tunnel floor, ground boards were used during the reflection plane tests.

Four different airfoils and wings were tested during the course of this investigation. Figure 1 shows the section profiles of the four different airfoils and wings tested. Table 1 lists the specifications for the airfoils and wings. The NACA 0011 symmetric airfoil, NLF 0414 straight wing, and NLF 0215 tapered wing were pitched about their quarter-chord location while the GA(W)-2 two-element airfoil was pitched about its half-chord location. The GA(W)-2 airfoil had 0.1-in.-wide transition strips made from #80 carborundum grit at the 5% chord locations of both the upper and lower surfaces of the main element. The NACA 0011 airfoil, NLF 0414, and NLF 0215 wings did not have transition strips.

Table 1 Airfoil and wing specifications

Profile	Type	Number of elements	Shape	Chord, ft	Span, ft	Other
NACA 0011	Two-dimensional	Single	Symmetric	2.0	3.0	——
GA(W)-2	Two-dimensional	Single/two	Cambered	2.0	3.0	25% slotted flap
NLF 0414	Three-dimensional straight	Single	Cambered	1.25	5.0 semispan	No dihedral
NLF 0215	Three-dimensional tapered	Single	Cambered	1.07 root 0.57 tip 0.85 mean	4.5 semispan	7-deg dihedral Sweep back: Leading edge = 0 deg Trailing edge = 6.3 deg

Table 2 Test conditions

Configuration	q, lb/ft^2	Chord Reynolds no.	Mach no.	α range, typical increment	Gurney height, % chord
NACA 0011 symmetric	25	2.2×10^6	0.13	−2 to +20, 1 deg	1, 2, 4
GA(W)-2 two-element	35	2.3×10^6	0.16	−8 to +16, 1, deg	1
NLF 0414 straight three-dimensional	20	1.2×10^6	0.12	−6 to +29, 1, deg	1.7, 3.3
	50	1.6×10^6	0.19	——	——
NLF 0215 tapered three-dimensional	25	0.9×10^6 (mean chord)	0.13	−10 to +24, 2, deg	1.2, 2.5 (% mean chord)

Table 2 specifies the test conditions of the various configurations investigated. In the case of the GA(W)-2 two-element airfoil, the 1% height Gurney flap was attached at the main element trailing edge, at the flap trailing edge, and at both locations as shown in Fig. 1b. In the case of the NLF 0414 straight wing, Gurney flaps of 1.5, 3.0, and 4.5 ft in span were located inboard, outboard, and at midspan as shown in Fig. 2. When the engine nacelle was attached to reflection plane model, the Gurney flap did not encompass the spanwise portion of the engine nacelle.

Results

Single-Element Airfoils

Figure 3 shows the aerodynamic load results for the single-element configurations. For the NACA 0011 configuration, the repeatability of the results from one test run to the next is very good for prestall angles of attack. Poststall results have some data scatter, which is to be expected from a separated flow environment. The effect of the Gurney flap is to increase the maximum lift coefficient as shown in Fig. 3a. This increase is most significant with a large Gurney flap and less profound with a small Gurney flap. The lift curves are shifted upward and to the left with the Gurney flap. Consequently, the angle of attack for zero lift becomes increasingly more negative as a larger Gurney flap is utilized. These results suggest that the Gurney flap serves to increase the effective camber of the airfoil. Figure 3 also shows that the stall angle is decreased as a larger Gurney flap is utilized. Table 3 lists the stall angle, maximum lift coefficient, and percentage increase in maximum lift coefficient for the various NACA 0011 configurations tested. Compared to the clean NACA 0011 airfoil, the maximum lift coefficient is increased 25, 36, and 47% for the 1, 2, and 4% height Gurney flaps, respectively.

Figure 3a shows that the lift increases in a linear fashion until stall for the symmetric NACA 0011 airfoil. On the other hand, the cambered GA(W)-2 airfoil exhibits a slight change in lift-curve slope as the angle of attack is increased. Abbott and von Doenhoff[16] show linear lift-curve slopes for symmetric airfoils. However, their data on some cambered airfoils, e.g., 24xx and 44xx series, exhibit changes in the lift-curve slope at low Reynolds number less than 3×10^6, similar to those seen in the GA(W)-2 results. Thus, the change in lift slope for the GA(W)-2 airfoil is attributed to the low Reynolds number (2.3×10^6) used in this test. The maximum lift coefficient obtained was 1.67 at an angle of attack of 16.2 deg for the clean GA(W)-2 airfoil in the nested configuration. This was

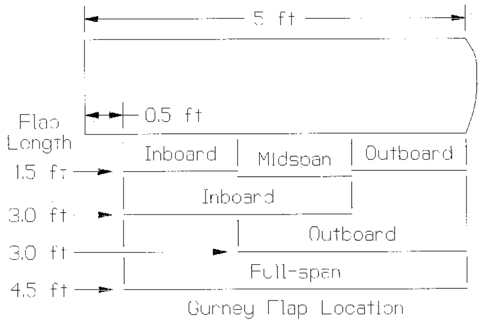

Fig. 2 Gurney flap locations on straight NLF 0414 wing.

Table 3 NACA 0011 Gurney flap performance

Gurney flap height	Stall angle, deg	Max C_l	Change in max C_l over baseline, %
Clean (no flap)	15.2	1.50	N/A
1%	14.2	1.88	25
2%	13.2	2.04	36
4%	12.2	2.20	47

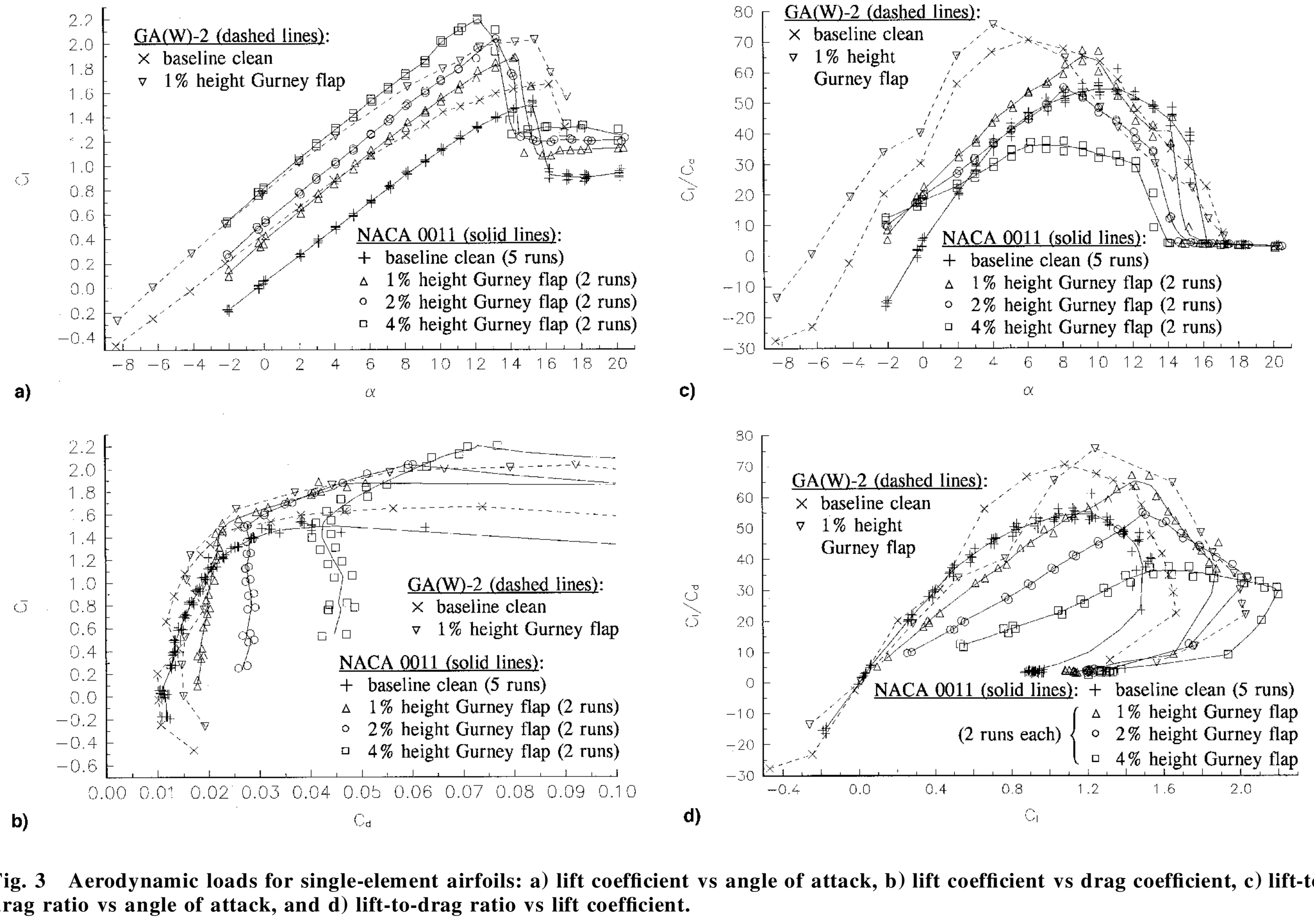

Fig. 3 Aerodynamic loads for single-element airfoils: a) lift coefficient vs angle of attack, b) lift coefficient vs drag coefficient, c) lift-to-drag ratio vs angle of attack, and d) lift-to-drag ratio vs lift coefficient.

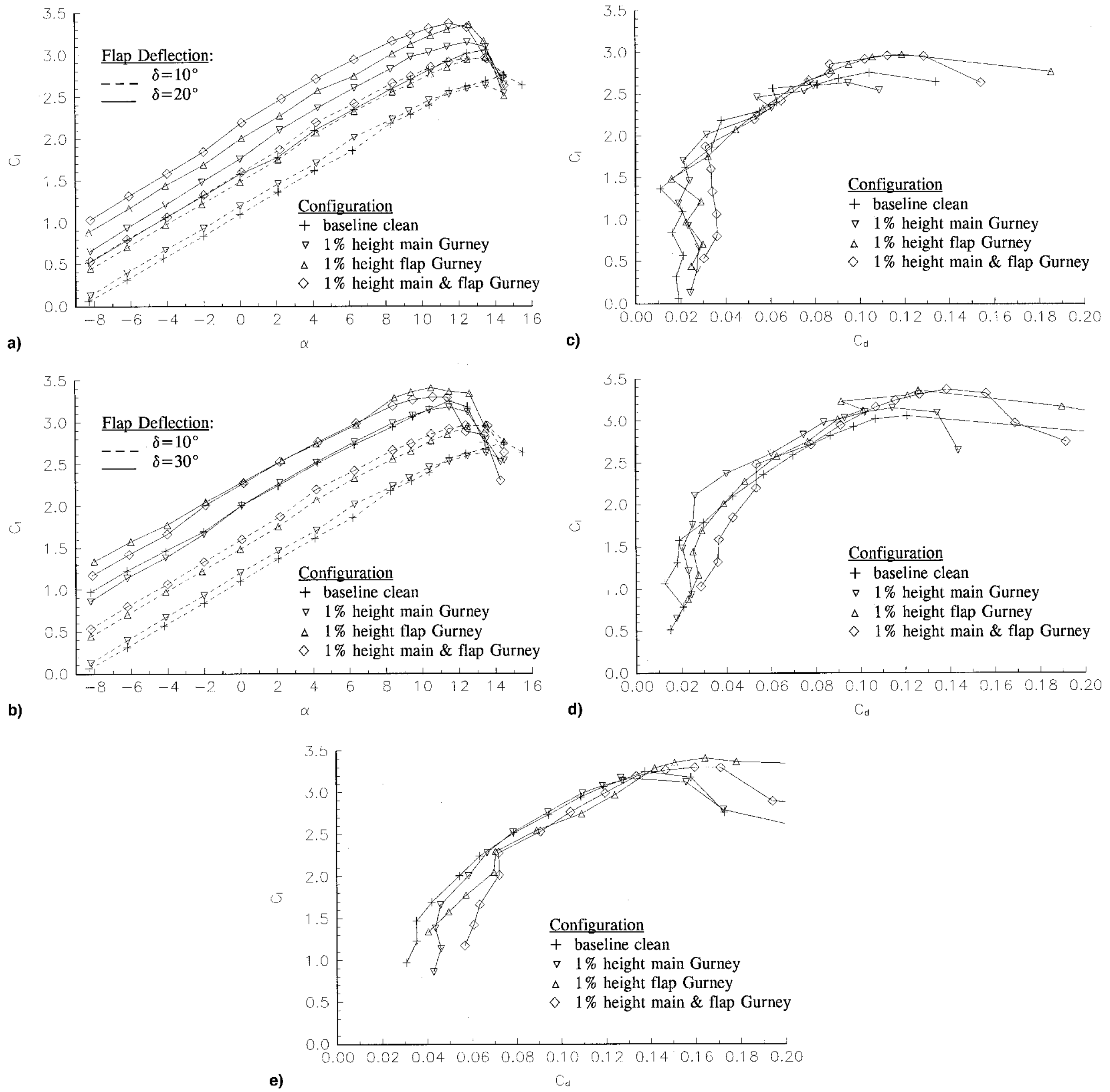

Fig. 4 Aerodynamic loads for GA(W)-2 two-element airfoil: lift coefficient vs a) angle of attack, b) angle of attack, c) drag coefficient for 10-deg flap deflection, d) drag coefficient for 20-deg flap deflection, and e) drag coefficient for 30-deg flap deflection.

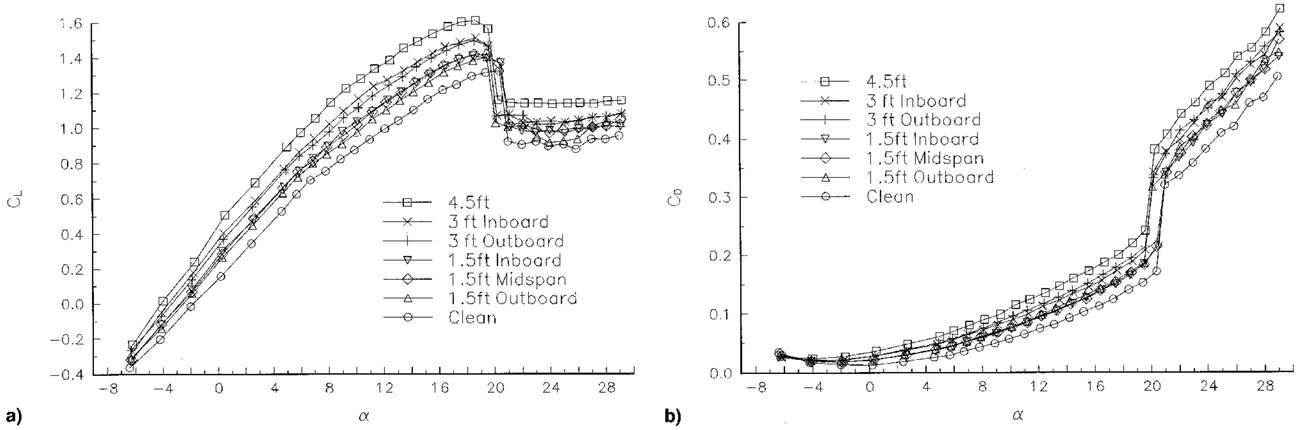

Fig. 5 Aerodynamic loads for NLF 0414 straight wing with 0.033c height Gurney flap at q = 20 lb/ft^2. See Fig. 2 for Gurney flap spanwise locations: a) lift and b) drag coefficients vs angle of attack.

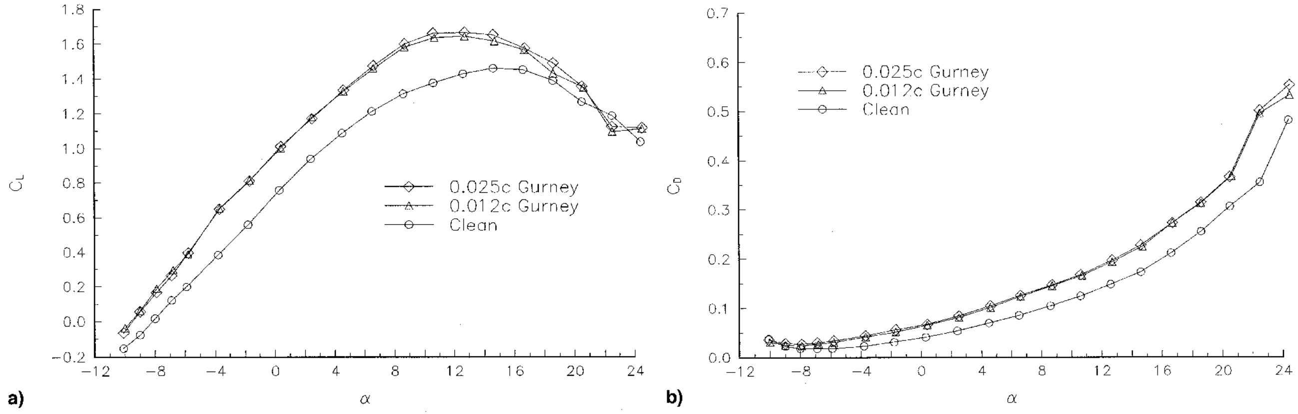

Fig. 6 Aerodynamic loads for NLF 0215 tapered wing: a) lift and b) drag coefficients vs angle of attack.

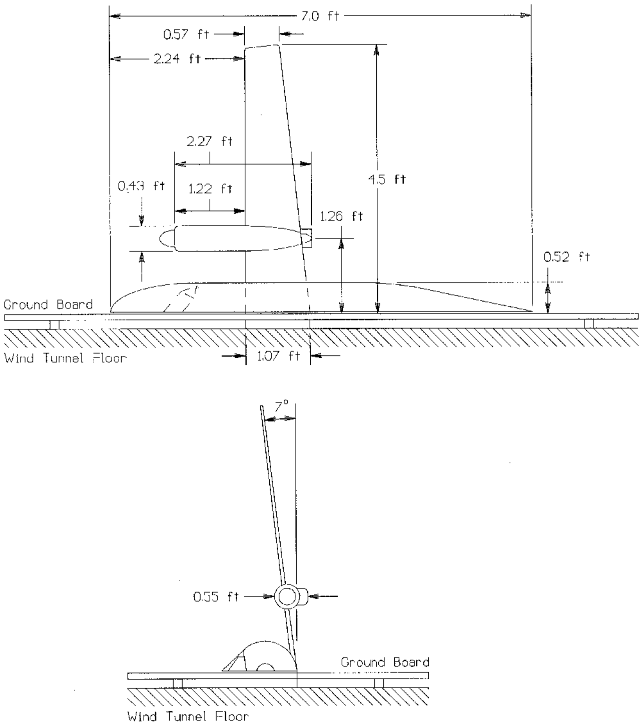

Fig. 7 Reflection plane model configuration.

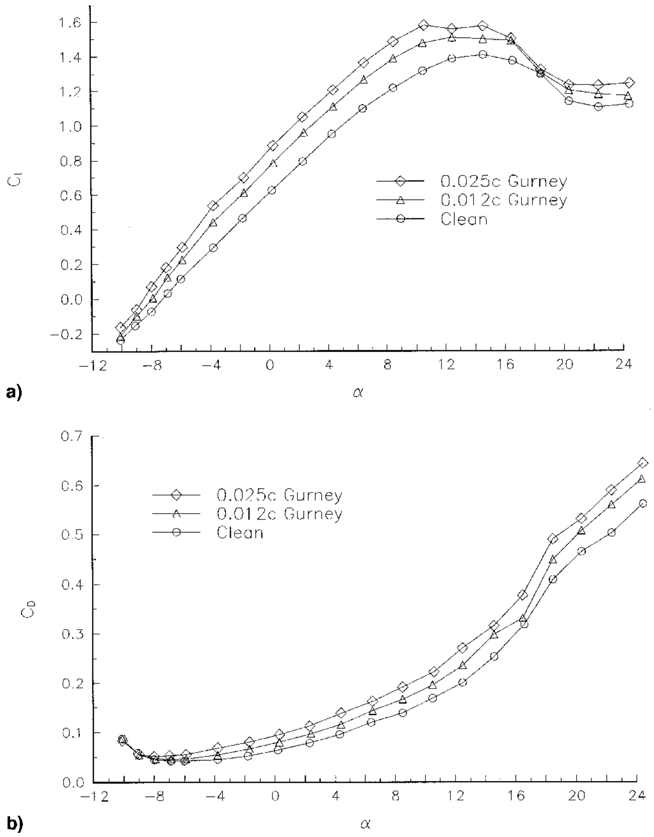

Fig. 8 Aerodynamic loads for NLF 0215 tapered wing with fuselage and nacelle: a) lift and b) drag coefficients vs angle of attack.

increased to a lift coefficient of 2.03 at an angle of attack of 15.4 deg when a 1% height Gurney flap was used, and this corresponds to a 22% increase in maximum lift coefficient compared to the baseline clean case.

The increase in lift obtained with the Gurney flap comes at the price of increased drag, as shown in Fig. 3b. At low- to moderate-lift coefficients, the Gurney flap produces more drag than the clean airfoil. This drag penalty is greater with the larger-size Gurney flap. At the higher lift coefficients, however, the Gurney flap is able to achieve a very high lift with less drag than the clean airfoil. Indeed, Fig. 3c shows that the 1% Gurney flap is able to achieve lift-to-drag ratios that are greater than the baseline clean case. It should be noted, however, that the baseline clean configuration still provides a better lift-to-drag ratio at low- to moderate-lift coefficients (typical cruise conditions) as shown in Fig. 3d.

Two-Element Airfoil

The 25% slotted flap on the GA(W)-2 airfoil was deflected at three different angles. Figure 4 shows the aerodynamic load results for the two-element airfoil. Results are shown for the baseline clean configuration as well as with the Gurney flap located at the main element cove, trailing element flap, and both elements. Figure 4a shows that there is a small gain in lift using a main-element Gurney flap in the 20-deg deflection configuration. However, Fig. 4b shows that very little additional lift is obtained using a main-element Gurney flap in the 10- and 30-deg deflection configurations. This is because the gap width and flow through the slot were originally optimized without the main-element Gurney flap in place. Figures 4c–4e show that the effect of the Gurney flap is to increase the drag at low- to moderate-lift coefficients compared to the baseline clean configurations. Using the Gurney flap, improved aerodynamic efficiency is only obtained at the high lift coefficients.

Three-Dimensional Wings

Figure 5 shows the lift and drag results for the NLF 0414 straight wing at a test Reynolds number of 1.2×10^6. Six different spanwise lengths and positions (Fig. 2) for the 0.033*c* height Gurney flap are shown in Fig. 5 along with the clean wing as the baseline comparison. Figure 5a shows that the effect of the Gurney flap is to increase the maximum lift coefficient. As expected, the larger increases in lift are obtained with the longer spanwise length Gurney flaps. This increase in lift is roughly proportional to the increase in spanwise length. For instance, the 1.5 ft spanwise length provided an increment in lift coefficient that is about one-third of the lift coefficient increment for the 4.5 ft spanwise length. The 3.0 ft spanwise length provided a lift coefficient increment that is about two-thirds of the increment for the 4.5 ft spanwise length. As a larger portion of the wing is covered by the Gurney flap, the stall angle decreases and the angle of attack for zero lift becomes increasingly more negative. These characteristics indicate an airfoil section with increased effective camber and are consistent with the observed results for two-dimensional airfoils with Gurney flaps.

Two new effects become evident for the three-dimensional wing that were not observed for two-dimensional airfoils. First, the lift and drag curve slopes are changed with the Gurney flap. This is different from the two-dimensional airfoil where the effect of the Gurney flap was to simply shift the curves (upward and to the left). Second, Fig. 5 shows that the inboard position for the Gurney flap provides a slight improvement in both lift and drag compared to the outboard position.

When the test Reynolds number was increased to 1.6×10^6 there was a slight increase in the maximum lift coefficient; otherwise, the effect of the Gurney flap is the same. In particular, the three-dimensional effects discussed earlier on the change in lift-curve slope and the improvement in performance with the inboard position were still evident at this higher Reynolds number.

Figure 6 shows the lift and drag results for the NLF 0215 tapered wing. Note that the Gurney flap height referenced here is based on the mean chord length. Thus, the Gurney flap height is actually 50% larger at the tip ($h = 0.018c$ and $0.038c$) and 20% smaller at the root ($h = 0.01c$ and $0.02c$). With the Gurney flap, the maximum lift coefficient is increased by 13% compared to the clean wing. The larger height Gurney flap, however, does not provide any added benefit in terms of lift increase compared to the smaller height Gurney flap. The reason for this behavior is not known at this time. Just like the straight wing case, the effect of the Gurney flap on the tapered wing is to change the lift and drag curve slopes rather than to simply shift the curves.

Reflection Plane Model

A fuselage body and engine nacelle were added to the NLF 0215 tapered wing. Figure 7 shows a schematic of the fuselage body and engine nacelle as mated to the NLF 0215 tapered wing. The fuselage had a radius of 0.52 ft, a length of 7.0 ft, and a frontal area of 0.852 ft^2. The engine nacelle had a width of 0.43 ft, a height of 0.55 ft, a length of 2.27 ft, and a frontal area of 0.150 ft^2. The nacelle was located at a spanwise location where the local wing chord length was 0.93 ft. Additional details about this twin engine reflection plane model are given in Ref. 17.

Figure 8 shows the lift and drag results with the fuselage and nacelle bodies attached. Again, the effect of the Gurney flap is to increase both the lift and the drag. However, the larger height Gurney flap was not as effective in increasing the lift coefficient as was the case for the two-dimensional airfoil sections.

Summary

The effect of Gurney flaps on two-dimensional airfoils, three-dimensional wings, and reflection plane model was investigated in the Wichita State University 7 × 10 ft low-speed wind tunnel. The symmetric NACA 0011 and the cambered GA(W)-2 airfoils were used during the single-element airfoil part of this investigation. The GA(W)-2 airfoil was also used during the two-element airfoil study with its 25% chord slotted flap deflected at 10, 20, and 30 deg. Straight and tapered reflection plane wings with NLF airfoil sections were tested during the three-dimensional wing part of this investigation. Fuselage and engine nacelle bodies were attached to the tapered NLF wing for the reflection plane model investigation.

Compared to the baseline clean configuration, the Gurney flap improved the maximum lift coefficient. There was, however, a drag penalty associated with this increase in lift. The Gurney flap provided an increase in lift on cambered as well as symmetric airfoils and on three-dimensional wings with and without aircraft bodies. Gurney flaps located at the cove region of the main element did not provide a significant improvement in performance when the trailing-element location of a two-element airfoil was optimized without a Gurney flap. A much larger improvement was obtained by attaching the Gurney flap on the trailing-edge element. On three-dimensional wings, there was a slight improvement in performance when the Gurney flap was located inboard rather than outboard.

Acknowledgements

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