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Two Aspects of the Use of Full- and Partial-Span Gurney Flaps

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Nomenclature

b	=	wing span, mm
c	=	wing chord, mm
C_D	=	wing drag coefficient
C_L	=	wing lift coefficient
D	=	wing drag, N
L	=	wing lift, N
N	=	number of vortex rollup visualization tufts in the primary vortex rope
RTF	=	vortex rollup tightness factor, N/x_s
S	=	wing reference area, mm²
w	=	uncertainty
x_s	=	distance from the wing trailing edge to the start of the primary vortex rope, mm
α	=	angle of attack, deg

I. Introduction

A GURNEY flap is a long and narrow plate attached to a wing's trailing edge on the pressure side and perpendicular to it. It is quite simple, yet very effective in bringing about significant changes in the flow around the wing. The primary effect is the added downward flow deflection at the trailing edge (thus, increased circulation). The wing $C_{L\max}$ increases: the larger the height of the flap, the more the lift improves. The wing drag, however, is also affected, almost always in the adverse way, and the overall effect on the wing L/D is detrimental.

The flap was first proposed and used successfully for race-car applications in the 1970s. In the same time frame, Liebeck [1] did an analysis of the device. Since then, a number of other researchers have studied various aspects of this modification. The following is a brief discussion of some of the most recent efforts. Zhan and Wang [2] studied the effects of Gurney flaps and apex flaps on the aerodynamic performance of a delta wing. They found that the Gurney flap produced a significant increase of C_L before stall accompanied by a drag penalty. Traub et al. [3] studied the effects of Gurney-flap porosity, inclination, and spacing on the wing's lift, drag, and moment characteristics. The same three authors conducted a preliminary study to examine the possibility of using a jet flap for hingeless control and compared the approach with a Gurney flap at the same location [4]. The tests showed noticeable lift augmentation, as well as C_D increase, throughout the range of α tested. Meyer, et al. [5] conducted investigations with the aim to stabilize the wake flow to achieve drag reduction. They used Gurney flaps with slits and holes and vortex generators. Their results showed the usual increases in both C_L and C_D. Although modifying Gurney flaps by adding holes had no effect on C_L, C_D was somewhat lowered, but still higher than that of the baseline wing. They supplemented their experiments by numerical simulation. The reader is referred to [6] for a short discussion of the most important work on the topic. Reference [7] gives a rather extensive review of the Gurney-flap research.

The present author has been studying Gurney flaps since 2004, primarily for their potential as a trailing-vortex-reduction device. This supposition is based on the following two premises [6]: First, the flap's ability to significantly alter the wing's lift, connected with the fact that a wing's lift and its trailing vortex are intimately related. Second, due to the spanwise components of the velocities of the airflows leaving a wing's trailing edge, which give rise to the sheet of vorticity that evolves into distinct trailing vortices downstream of the generating wing, it appears reasonable to wonder: What effect might a Gurney flap have on the spanwise flow direction as the flow leaves the wing's pressure side at the trailing edge? Would the presence of the flap impede the flow? A single Gurney flap was tested in combination with a rectangular wing. Using oil-smoke flow visualization and a newly proposed model of a vortex rollup tightness factor (RTF), it was shown that the flap did affect the trailing vortex rollup in the near field [6].

To bring closer Gurney-flap and wing wake vortices a study was conducted to address the supposition that, according to the Helmholtz vortex laws, the presence of a Gurney flap (as with any flap, for that matter) must lead to the creation of additional trailing vortices [7]. The flow hypothesis of [1] makes no reference to these vortices. The study clearly confirmed the existence of such vortices [7]. With these vortices confirmed, the reasoning that Gurney flaps may affect the wake rollup appeared even more justified. Subsequently, two additional full-span Gurney flaps of varying height were investigated [8]. As might be suspected, the results showed that the higher the Gurney flap, the more pronounced its effect on the wing aerodynamics and also on trailing vortex reduction in the near field.

Following the findings of these three studies, while considering the mechanism through which a Gurney flap increases a wing's C_L, the following appeared a reasonable question: Would a part-span flap installed at various spanwise locations be able to produce the desirable vortex reduction with a lower increase of the wing's drag and weight? The plausibility of this supposition in the case of a rectangular wing seemed to be enhanced by the well-known separation pattern on this planform. It seemed justifiable to assume that a Gurney flap positioned around the wing's centerline would help most by energizing the suction-side airflow as α is increased. How effective would a flap positioned outboard be in energizing the still attached flow? Also, can a flap installed in this way create trailing vortices capable of interfering with the main wingtip vortices? Based on these thoughts, it seemed warranted to commence a study with the objective to examine these flow phenomena. Apparently, the next question involved the effects of the trailing vortices originating at the flap's ends. The study presented in this paper was undertaken with the goal to address these questions.

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II. Models and Experiments

The experiments for this study were conducted in a low-speed wind tunnel at Minnesota State University, having a test section of 305 mm square, capable of generating flows of up to 45.7 m/s. A detailed description of the tunnel and its instrumentation can be found in [9].

The models included a rectangular wing having a NACA 4412 airfoil with a span of 161 mm, a chord of 99.6 mm, and three models of Gurney flaps. All three flaps had a height of $0.06c$. The first flap had a span equal to $1.0b$, the second flap's span was $0.5b$ and was attached to the outboard half of the wing, and the third flap had a span also equal to $0.5b$, but it extended over the inner half of the wing. The following designations are used: BLW is the baseline wing, GF06FS is the wing with the full-span Gurney flap, GF06.5O is the wing with the outboard half-span flap, and GF06.5I is the wing with the inboard half-span flap.

The flaps and attachment brackets were manufactured from a 0.762-mm-thick aluminum sheet. A photograph of the GF06.5O model in the test section is shown in Fig. 1.

All of the tests were conducted at a Reynolds number of approximately 0.225×10^6 based on c so that the generated lift forces would remain within the limits recommended by the balance's manufacturer. The contribution to the model drag by the strut was subtracted. The experiments included α between 3 and 15 deg with 1-deg increments. This range is chosen because it was shown that the RTF correlated with the vortex strength very well in this range of α [6,8].

First, each configuration was run at the α from the range, and L and D were measured. Next, eleven tufts were added along the wing's trailing edge of the port (left) semispan. The tufts are made from yarn, with a diameter of 0.1 mm and length of $1.5b$, and they were spaced uniformly, $0.05b$ apart. Five runs at each α from the range were conducted. At the end of each run, the number of tufts N entrained in the primary trailing vortex was determined, and the distance x_s from the wing's trailing edge to the start of the vortex was measured. With these two parameters, a vortex RTF was calculated as $\mathrm{RTF} = N/x_s$ [6]. The value of the RTF at each α was then calculated as the simple average of the five individual values.

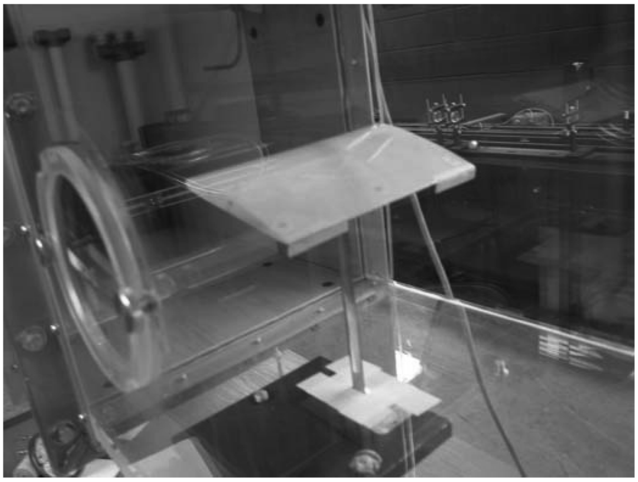

Fig. 1 Model of a wing with Gurney flap GF06.5O in the test section.

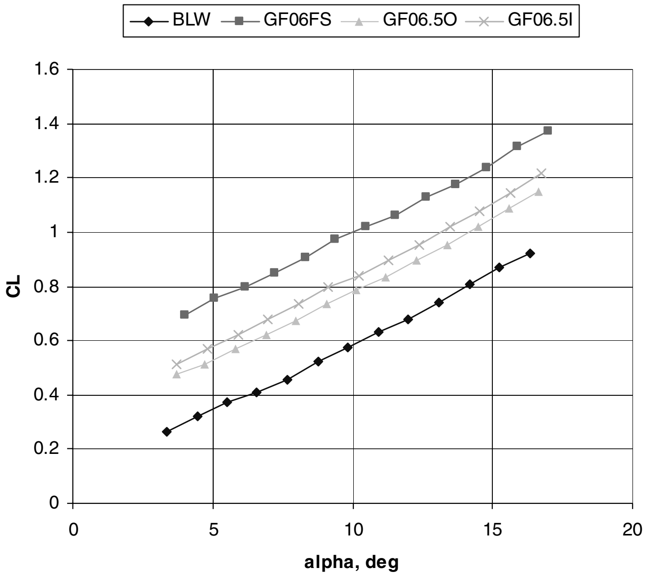

Fig. 2 Effect of the Gurney-flap span and location on the wing lift coefficient.

III. Discussion of Results

A. Effects on Lift and Drag

The lift and drag data were corrected for solid and wake blockage and general downwash effects, including the lift distribution [10]. These results are shown in Figs. 2–4 and summarized in Table 1 for $\alpha_{\mathrm{uncorr}} = 15$ deg. It can be seen that the addition of the flaps dramatically improved the wing's lift, with the full-span flap producing the largest increase. It is also seen that the GF06.5I is the most efficient flap among the three tested in terms of additional lift production per unit flap span. Of the two half-span flaps, the GF06.5I produced higher C_L at all values of α. The reason for this is believed to be in the added downward momentum (thus, energy) to the airflow over the wing suction side around midspan locations at which the flow slows down first on a rectangular wing.

Figure 3 shows the effects on the wing C_D. Two conclusions can be made based on this figure. First, as is clear from Fig. 2, the available C_L increases significantly with the addition of the flaps. Second, the drag polars for the flapped wing configurations have shifted upward and to the right, while remaining almost equidistant with the BLW curve and among themselves. This would indicate that the ensuing drag increases are due to the increased zero-lift drag, rather than the induced drag, which would agree well with the fact that the aspect ratio remained the same for all the configurations.

Figure 4 shows the combined effects of the flaps on the wing L/D. It can be seen that the aerodynamic efficiencies of all three flapped configurations suffer from the addition of the flaps. The highest values of L/D found are given in Table 2.

As an illustration, a comparison of L/D at an approximately constant C_L is given in Table 3. The value chosen for C_L is around 0.9, because this is the highest value attainable with the BLW.

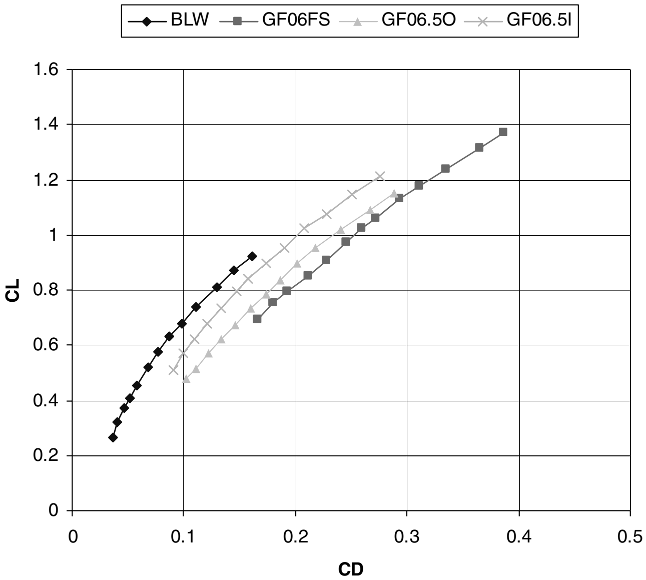

Fig. 3 Effect of the Gurney-flap span and location on the wing drag coefficient.

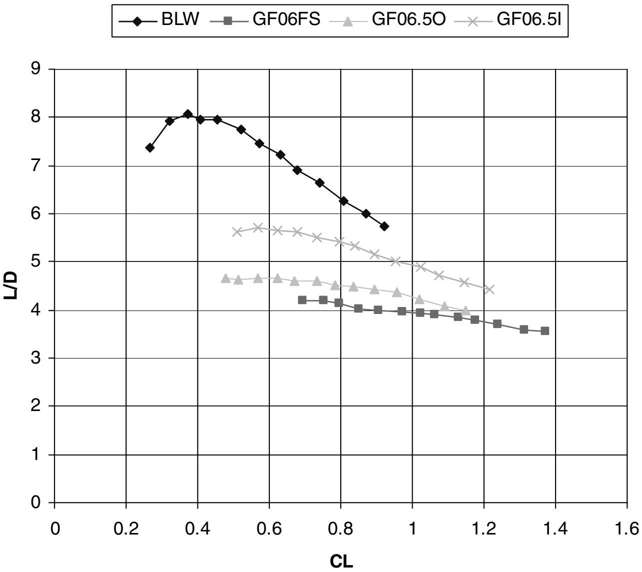

Fig. 4 Effect of the Gurney-flap span and location on wing aerodynamic efficiency.

The reason this large flap was chosen lies in the desire to be able to identify the effects that a Gurney flap may have on trailing vortex development and strength [6]. It is also noted that a level of decrease in L/D might be acceptable during those phases of flight when wake vortices are critical and the high L is more important than high L/D (such as, for example, during the approach for landing, when a lower L/D is often desirable).

Table 1 Effects of Gurney flaps on wing aerodynamics ($\alpha_{uncorr} = 15$ deg and Δ = relative change, %)

Configuration	C_L	ΔC_L	C_D	ΔC_D	L/D	$\Delta(L/D)$
BLW	0.921	——	0.1607	——	5.73	——
GF06FS	1.371	48.9	0.3866	140.6	3.55	−38.0
GF06.5O	1.150	24.8	0.2879	79.2	3.99	−30.4
GF06.5I	1.215	31.9	0.2753	71.3	4.41	−23.0

Table 2 $(L/D)_{max}$

Configuration	L/D	α_{uncorr}, deg
BLW	8.08	5
GF06FS	4.19	3
GF06.5O	4.66	3
GF06.5I	5.70	4

Table 3 Effect of Gurney flaps on wing L/D at $C_L \approx 0.9$

Configuration	C_L	α_{uncorr}, deg	L/D	$\Delta(L/D)$
BLW	0.921	15	5.73	——
GF06FS	0.971	8	3.95	−31.1
GF06.5O	0.955	12	4.38	−23.6
GF06.5I	0.953	11	5.02	−12.4

Table 4 Representative RTF results for GF06.5I

α_{uncorr}	15 deg, reset	15 deg, fixed	10 deg, reset	3 deg, reset
Run 1	0.1077	0.0899	0.0962	0.0717
Run 2	0.1013	0.0962	0.0909	0.0678
Run 3	0.1014	0.0952	0.0893	0.0727
Run 4	0.1046	0.1026	0.0870	0.0727
Run 5	0.1034	0.1111	0.0893	0.0784
Mean	0.1037	0.0990	0.0905	0.0727
Median	0.1034	0.0962	0.0893	0.0727
Std dev	0.0026	0.0081	0.0034	0.0038

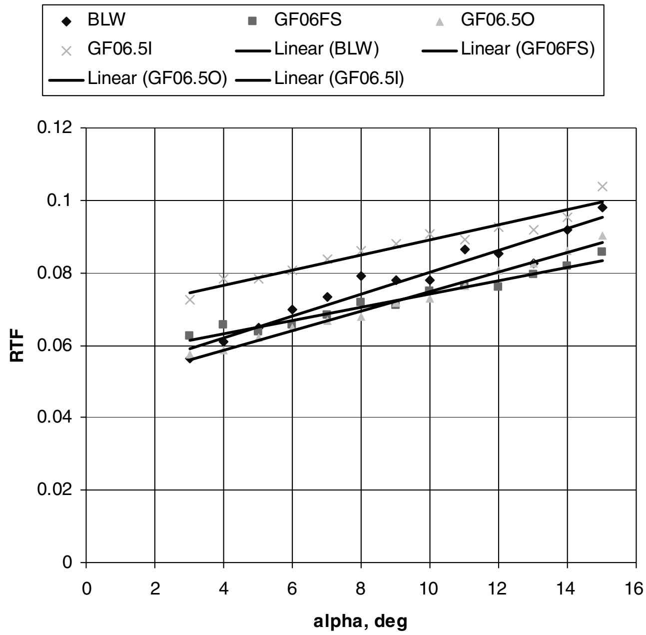

Fig. 5 Effect of the Gurney-flap span and location on the rollup tightness factor.

Because of the force-balance limitation (it has only L and D components) the changes in pitching moment, typical of Gurney flaps, could not be examined. The additional pitching moment increases the trim drag. Thus, the preceding comparisons of aerodynamic performance would eventually need to include this effect.

B. Effects on Trailing Vortex Strength in the Near Field

Once the lift and drag measurements for a configuration were completed, the flow visualization tufts, described earlier, were added. Five runs per each α were done and the model α was reset before each run.

First, it is noted that the RTF method continued to yield very good results, preserving the trends previously shown [6,8]. To illustrate this, some results for the GF06.5I were arranged in Table 4. The second column gives the values for the runs with α reset between runs; the data in the third column are for fixed α. It is noted that the two means differ by only 4.5%. These results are remarkable, considering the simple nature of the RTF method.

The RTF results are shown in Fig. 5. It can be seen that the set of data points for each configuration quite closely followed a straight line, as they should [6]. The GF06FS brought about a significant change in the near-field vortex strength, producing lower values of the RTF (i.e., weaker trailing vortices in the near field) over most of the range of α than the BLW. If $\alpha = 15$ deg is considered as being representative of takeoff, when the trailing wake vortex problem is the most critical, then the vortex strength reduction due to the employment of this full-span Gurney flap would amount to 12.7%. It should be pointed out that this level of attenuation is different from that reported in [6]; the study reported therein involved the original strut and shroud, which produced spurious midspan vortices. The GF06.5O configuration produced a reduction of 7.95% at $\alpha = 15$ deg. It is noted that the partial-span flap is more effective on a per-unit-flap-span basis. This combined with the less-detrimental effect of this flap on the wing L/D would suggest that improvements should be sought among partial-span flaps located outboard. However, the foremost caveat that applies to these conclusions is in the near-field character of the study. Therefore, the study needs to be carried into the far field.

The results pertaining to the GF06.5I are rather interesting, although not unexpected. This flap would actually increase the strength of the trailing vortex in the near field. The increase at $\alpha = 15$ deg was approximately 5.8%. The reason this result is not surprising is because all RTF test runs involving this configuration

Table 5 Representative uncertainties for the BLW

	$\alpha = 5$ deg	
Coefficient	C_L	C_D
Value	0.374	0.0428
w	0.9%	5.9%
Lower bound	0.357	0.0370
Upper bound	0.388	0.0484
Δ_{lower}	−4.5%	−13.6%
Δ_{upper}	3.7%	13.1%
	$\alpha = 15$ deg	
Coefficient	C_L	C_D
Value	0.921	0.1394
w	0.8%	1.9%
Lower bound	0.903	0.1318
Upper bound	0.943	0.1462
Δ_{lower}	−2.0%	−5.4%
Δ_{upper}	2.4%	4.9%

Table 6 RTF uncertainty of the BLW at $\alpha = 15$ deg

RTF	0.0972
w_{RTF}	0.7%
Upper bound	0.0986
Lower bound	0.0959
Δ_{upper}	1.44%
Δ_{lower}	−2.1%

showed two additional vortices emanating from the flap edges and having the same sense of rotation as the main wing vortices, as previously reported in [7]. It appears that these vortices contribute to the tightening of the wing trailing vortices. In the past, researchers have proposed to attenuate the wing trailing vortices by injection of discrete midspan vortices [11,12]. Those ideas involved far-field vortex interactions. The mechanisms involved were quite different from the near-field effects of this study. It should be kept in mind that the Reynolds number for these experiments was low; increasing it may affect these conclusions. Thus, further tests at higher Reynolds numbers are necessary. Additionally, pragmatic considerations should be included.

IV. Experimental Uncertainties

The following are estimates of the experimental uncertainties involved in this study. The α of the wing could be determined to within ± 0.25 deg. All lengths are reliable to within ± 0.5 mm, except x_s, for which the uncertainty was ± 1.0 mm. The dynamic pressure is accurate to within ± 0.005 kPa. The L and D readouts are considered reliable to within ± 0.05 N.

These represent the absolute upper and lower bounds. The uncertainties for these variables, with the odds of 20:1, were estimated to be one-half of these values (for example, $w_L = w_D = 0.025$ N, etc.). Using these estimates, the uncertainties of the results were determined using the second-power equation of Kline and McClintock [13]. The uncertainties associated with C_L and C_D at $\alpha = 5$ deg, which corresponds to $(L/D)_{\max}$, and at $\alpha = 15$ deg for the BLW were calculated. Also, the absolute upper and lower bounds for those coefficients were estimated. These results are given in Table 5.

Several conclusions can be made based on this table. First, the uncertainties are far less than the upper or lower bounds. Second, the C_D uncertainty is higher than that of C_L. This is due to the fact that the values of D are much less than those of L. Third, the uncertainties decrease as α increases, because of the higher forces at higher α.

The uncertainty estimates for the RTF of the BLW at $\alpha = 15$ deg are given in Table 6. The value is calculated as $\text{RTF} = N/x_s = 7/72 = 0.0972$. This run was very close to the five-point average of 0.0981, which, with $N = 7$, would correspond to $x_s = 71.4$ mm.

The absolute amount of this uncertainty is 0.0007. Because out of the two variables involved, one (N) is exact, thus w_{RTF} will be quite low. The same result of $w_{\text{RTF}} = 0.7\%$ was obtained for the smallest RTF value obtained in the study ($\text{RTF} = 4/72 = 0.0556$ for the BLW at $\alpha = 3$ deg). However, the absolute amount of this uncertainty is 0.0004. Thus, the RTF values were calculated to four decimal places.

V. Conclusions

An experimental study of two aspects of the use of Gurney flaps of various spans with a rectangular wing model was conducted. One full-span flap and two flaps each having a span equal to one-half the wing span, one placed inboard and the other placed outboard, were investigated in a low-speed wind tunnel with the objective to determine the effects that these flaps have on the development and strength of the trailing wake vortices and the wing's lift and drag characteristics. As expected, the addition of the flaps dramatically changed the lift and drag, such that the lift-to-drag ratio decreases, with the effect increasing with flap span. Of the two one-half-span flaps, the one positioned inboard generated higher lift coefficient as well as lower drag coefficient at the same lift coefficient. Although superior in terms of its aerodynamic performance, this flap increased the trailing vortex strength in the near field by 5.8% relative to the baseline wing. The full-span flap and the half-span flap located outboard were successful in attenuating the vortex strength by producing a 12.7 and 7.9% reduction, respectively. Therefore, it was concluded that an acceptable solution from the standpoint of both vortex strength reduction and wing performance degradation, should be sought among partial-span Gurney flaps installed outboard. Further studies involving other planforms and higher Reynolds numbers are needed to fully explore the effect of the relative span of outboard flaps and to expand the analysis into the far field.

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