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Engineering Notes

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Trailing Vortex Rollup from a Wing Equipped with a Gurney Flap

Vojin R. Nikolic†
Minnesota State University, Mankato, Minnesota 56001

Introduction

TRAILING vortices and the hazard they pose to following aircraft have been studied by many researchers since the 1970s.[1] Although many attempts to minimize the wake vortex problem have been examined, the strong adverse effect on the performance of the wake generating airplane has precluded their use. The present work explores the use of a Gurney flap as a wake vortex alleviation device.

A Gurney flap is a narrow rectangular plate that is installed at the trailing edge of a wing on its pressure side as shown in Fig. 1. The typical height of the Gurney flap is 1–5% of the wing chord. The flap was first introduced by Gurney in the 1970s to improve the cornering speeds of racecars. Liebeck[2] studied the effect of the Gurney flap on the performance of a Newman airfoil and found that a flap with a height of $0.01c$ increased the lift and decreased the drag. Storms and Jang examined the effect of a Gurney flap and/or vortex generator on the performance of a rectangular wing.[3] They reported an augmentation of lift with Gurney flaps; this augmentation increased with increasing flap height. Ashby examined the effects of the height and location of Gurney flaps on the lift, drag, and pitching moment characteristics of a two-element rectangular wing.[4] The effects of Gurney flaps on airfoils, wings, and a reflection plane model were investigated by Myose et al.[5] The Gurney flap improved $C_{L,\max}$ of the flap-equipped configurations compared to the baseline configurations.[5] Jeffrey et al. studied a single-element wing fitted with a Gurney flap.[6] The Gurney flap increased the lift at a given prestall angle of attack but increased drag at most values of C_L. Despite a reduction in the stall angle of attack, the Gurney flaps increased $C_{L,\max}$. Buchholtz and Tso studied the effects of leading-edge fences and Gurney flaps, both separately and in combination, on the performance of a 60-deg delta wing.[7] The Gurney flap was observed to increase the lift. Li and Wang tested delta wings with and without riblets and Gurney flaps.[8] They found that all Gurney flaps increased C_L and the larger flaps were more effective. Gai and Palfrey conducted experiments on a wing equipped with $0.05c$ Gurney flaps; both solid and serrated Gurney flaps were examined.[9] Both flaps increased the lift, but reduced the stall angle of attack. The $(L/D)_{\max}$ for both configurations was about 7% less than for the baseline configuration. Lin et al.[10] tested a rectangular wing with a Gurney flap. The effects of the angle between the wing's pressure surface and the flap and the distance between the flap and the wing trailing edge were studied. They found that all Gurney flap configurations increased the lift; the largest $C_{L,\max}$ was obtained with a flap angle of 90 deg. When shifted forward from the trailing edge, the Gurney flap was observed to be less effective in increasing lift.

In contrast to the previous studies that examined the effect of the Gurney flap on the aerodynamic performance, the present work assessed the potential use of the Gurney flap as a device for vortex alleviation. This is motivated by the knowledge that the lift of a wing and its distribution of circulation are directly linked. Because the Gurney flap modifies the lift, it is of interest to examine the nature of the modification to the trailing vorticity. The flow at the trailing edge of a wing may be modeled as a series of vortex filaments as shown in Fig. 2. In the present work, tufts are employed to visualize the nature of this flow at the trailing edge. Whereas tuft flow visualization, described in detail in Refs. 11 and 12, has been primarily used qualitatively, the present work shows that tufts can be used to assess vortex strength quantitatively in the wake of a wing. The response of tufts, placed at the trailing edge of the wing, to the flow is schematically shown in Fig. 3. This response can be

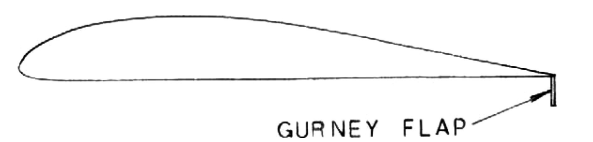

Fig. 1 Wing with Gurney flap.

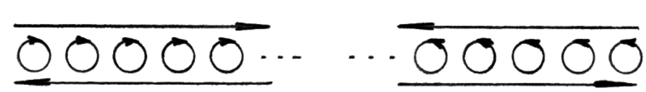

Fig. 2 Flow at wing trailing edge.

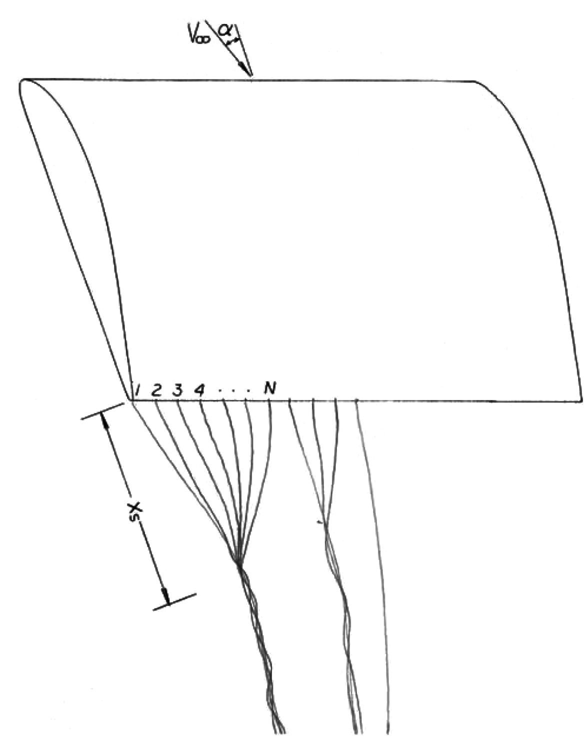

Fig. 3 Parameters related to the RTF.

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†Professor, Department of Mechanical Engineering. Senior Member AIAA.

quantified by two measurable parameters: the number of tufts, N, that are entrained over the outboard portion of the wing span and the distance x_s measured from the trailing edge to the location where the individual tufts are entrained into a single vortex. As the strength of the trailing vortex increases, N increases and x_s decreases. Thus, the ratio of N and x_s, termed here as the rollup tightness factor (RTF)

$$\mathrm{RTF} = N/x_s \tag{1}$$

is directly related to the vortex strength.

The analysis that is next presented shows the relationship between the strength of the trailing vortex, as measured by RTF, and the wing's lift. The lift is given by

$$L = \tfrac{1}{2}\rho_\infty V_\infty^2 C_L S \tag{2}$$

where ρ_∞ is the freestream density, V_∞ the freestream velocity, and S (the product of the wing span b and wing chord c for a rectangular wing) is the wing reference area. From the Kutta–Joukowski theorem, the lift is also related to the distribution of the circulation by

$$L = 2\int_0^{b/2} \rho_\infty V_\infty \Gamma(y)\,\mathrm{d}y = b'\rho_\infty V_\infty \bar{\Gamma} \tag{3}$$

where $\bar{\Gamma}$ is the average value of the bound vortex circulation and b' is the vortex span. When Eqs. (2) and (3) are compared, note that

$$\bar{\Gamma} = \tfrac{1}{2}(b/b')V_\infty c C_L \tag{4}$$

or

$$\bar{\Gamma} = C_1 \times C_L \tag{5}$$

where C_1 is a constant for a given freestream velocity. (Note that b' is constant for a given bound vortex distribution because the first moment of vorticity is conserved). Because RTF is a measure of the vortex strength, it is evident from Eqs. (1) and (5) that

$$\mathrm{RTF} = C_2 \times C_L \tag{6}$$

where C_2 is a constant. That is, there is a direct proportionality between RTF and C_L, at least over the liner portion of the C_L–α curve.

In the following sections, the experimental setup and results that illustrate the use of RTF to characterize the effectiveness of the Gurney flap as a vortex alleviation device are presented.

Experimental Setup and Procedure

The experiments were conducted in the open-circuit wind tunnel at Minnesota State University. The dimensions of the test section are 305 by 305 mm, and the maximum speed is 45.7 m/s. A more detailed description of the tunnel is given in Ref. 13.

The rectangular wing model has a NACA 4412 airfoil with a chord of 99.6 mm and a span of 161.5 mm. For the present tests, the Reynolds number based on the chord is 0.25×10^6. The Gurney flap has a height of 0.06c and extends across the span of the wing. The Gurney flap is located at the trailing edge and is mounted perpendicular to the pressure surface. Both the baseline, that is, no Gurney flap, and Gurney flap configurations are instrumented with tufts along the wing's trailing edge. The tufts are made from yarn, which has a diameter of 0.1 mm and length of 242 mm. The tufts are uniformly spaced, 8 mm apart, across the port semispan. The effect of tufts on the aerodynamic forces is described in Ref. 14. A force balance is used to measure the aerodynamic forces directly.

Measurements are made on the baseline and flapped configurations over a range of 3–15 deg angle of attack. Six separate runs are performed at each angle of attack; during each run N and x_s are measured.

Experimental Uncertainties

The following are estimates of the experimental uncertainties. The angle of attack of the wing is determined to within ±0.25 deg. All lengths are reliable to within 0.5 mm. The dynamic pressure is accurate to within ±0.1 kPa. The lift and drag force readouts are reliable to within ±0.05 N.

Discussion of Results

Figures 4 and 5 show typical tuft flow visualization results for the baseline and flapped wing configurations, respectively.

Figure 6 shows RTF vs angle of attack for the baseline wing. The symbols show the experimental data, and the line shows the least-square linear fit to the data. As suggested by the preceding analysis,

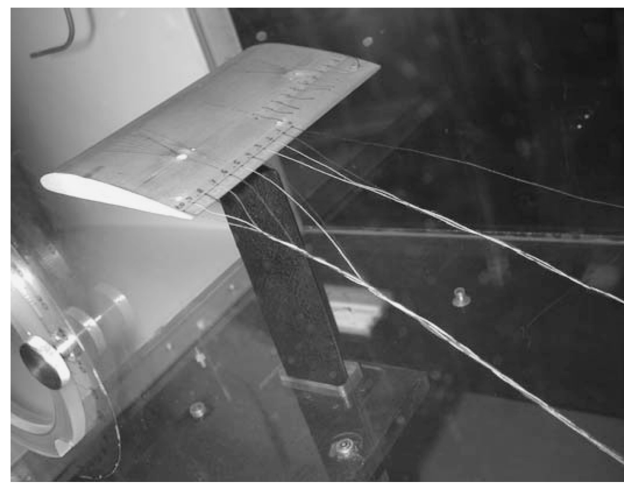

Fig. 4 Tuft flow visualization for baseline configuration; 12-deg angle of attack.

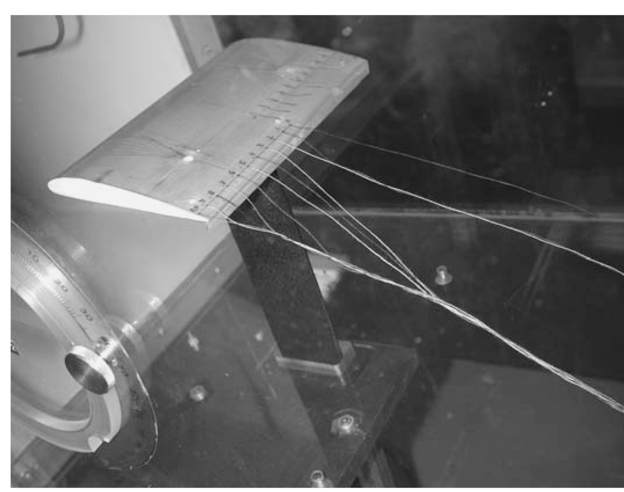

Fig. 5 Tuft flow visualization for wing with Gurney flap; 12-deg angle of attack.

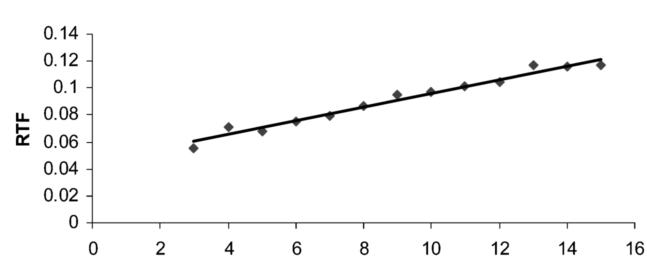

Fig. 6 RTF for baseline wing, α = 3–15 deg: ♦, data and ——, linear (data).

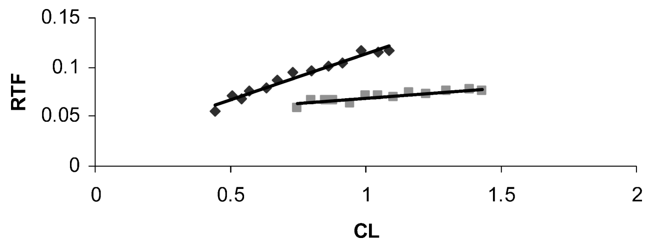

Fig. 7 Effect of Gurney flap on RTF: ♦, baseline wing; ——, linear (baseline wing); ■, wing with Gurney flap; and ——, linear (wing with Gurney flap).

RTF varies linearly with angle of attack. The effect of the Gurney flap is evident in Fig. 7 where RTF vs C_L is shown for the baseline and Gurney flap wing configurations. Again, the symbols show the data and the lines show the best linear fit. It can be seen that for a given lift coefficient RTF is smaller for the flapped configuration compared to the baseline condition. This is indicative of alleviation of the trailing vortex due to the Gurney flap. Also note that the slope of RTF vs C_L best-fit line for the Gurney flap configuration is less than for the baseline configuration. This indicates that the effectiveness of the Gurney flap is maintained over a wide range of angle of attack, up to the critical angle of attack.

Conclusions

An experimental study of the potential use of a Gurney flap as a trailing vortex alleviation device has been conducted. Quantitative measurements from tuft flow visualization are used to measure the strength of the vortices in the trailing-edge flow region. The measurements show that, up to the critical angle of attack, the Gurney flap is an effective trailing-vortex alleviation device.

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