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Engineering Notes

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Effect of Full-Span Gurney Flap Height on Wing Wake Vortex Alleviation

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Introduction: Wake Vortex Hazard and Gurney Flaps

THE hazard posed by wake vortices trailing behind heavy airplanes to following aircraft has been well known, and the area has been researched to considerable depth since the introduction of the first jumbo jets in the early 1970s. The reader is referred to [1] for an outstanding review of the subject area. The present author has been active in this area since the early 1990s. Gurney flap is an aerodynamic concept that dates back to the 1970s. It represents a long and narrow plate placed at a wing's trailing edge on its pressure side and perpendicular to it. It was first proposed and utilized quite successfully by Dan Gurney as a means to increase the downforce on his racing cars. The concept has received some attention in the aerospace community; see, for example, [2–12], with rather limited implementation in actual airplane wing design. For a rather extensive review of Gurney flap-related research the reader is referred to [13]. It will be stated here only that the flap regularly increases both the wing's lift and drag and decreases its aerodynamic efficiency. The major effect of this modification is an increased circulation at the wing trailing edge.

Since early 2004 the author has been studying the potential use of Gurney flaps for wake vortex alleviation. First, a Gurney flap having a height equal to 6% of the wing chord was studied. Several flow visualization techniques were used to qualitatively compare the near-field wake flows behind a baseline wing vs a Gurney flap equipped wing [13]. A new quantitative description of the vortex strength, a roll-up tightness factor (RTF) was proposed and used. It was found that the flap indeed affected the near-field wing wake to a significant degree [14]. Next, an additional Gurney flap, one having a height equal to 1.5% of the wing chord, i.e., $0.015c$, was investigated [15]. The results followed the trends presented in [13,14] quite well. To further expand the investigation matrix, an intermediate-height Gurney flap, one with a height equal to $0.04c$, has been examined recently. Once again, both the effects on the aerodynamic characteristics of the configurations and their respective vortex strengths have been recorded and analyzed. A discussion of these results is presented in the next sections.

Wind Tunnel Models and Test Procedure

The baseline configuration for this study involved a rectangular wing having a NACA 4412 airfoil with a chord of 99.6 mm and a span of 161.5 mm. The force measurement tests have been completed with a clean wing, whereas for the flow visualization portions of the experiments the wing has been instrumented with a series of 11 tufts, or strings of thin polyester thread having a length of 242 mm each, which corresponds to one and one-half wing spans. The tufts have been attached to the wing at its trailing edge along the port semispan with 0.1 of the semispan between successive tufts. To aid in observing the trailing vortex roll-up patterns the tufts have been selected of different colors. Before each run the tufts were carefully unrolled.

Three Gurney flaps have been used. The flap heights equaled 1.5, 4, and 6% of the wing chord. They have been fabricated from a 0.762 mm-thick aluminum sheet together with attachment brackets, three per flap. Figure 1 shows the baseline wing, "clean," along with the three Gurney flaps, a short section of the wing, or the "airfoil," and the three attaching screws. No gap existed between the wing and the flaps when installed.

The tests have been conducted in the open-circuit wind tunnel at Minnesota State University. It has a test section of 305 mm square and is capable of producing speeds up to 45 m/s. A more detailed description of the tunnel and its instrumentation can be found in [16]. For the force measurement portions of the study the Reynolds number based on the wing chord has been maintained constant at approximately 0.25×10^6. The flow visualization observations have been conducted at the tunnel's minimum speed of approximately 4 m/s. Occasionally good quality photographs of the ensuing vortex rollups have been taken using a digital still camera.

First, the standard force measurements have been conducted. The models have been tested at angles of attack $\alpha = 3–15°$. The reason for selecting this range lies in the objective of the study: to investigate wake vortex alleviation using Gurney flaps. Since the wing stalled at around 18°, it was felt that the vortex studies should be conducted up to 15°. Next, flow visualization tufts were installed and the models run 5 times at each α, with an exception of 15° at which angle 10 runs were conducted rather than, and occasionally in addition to, the usual five. The values of RTF were calculated as described below.

The following are estimates of the uncertainties associated with all the experimental variables involved in the study. The angle of attack

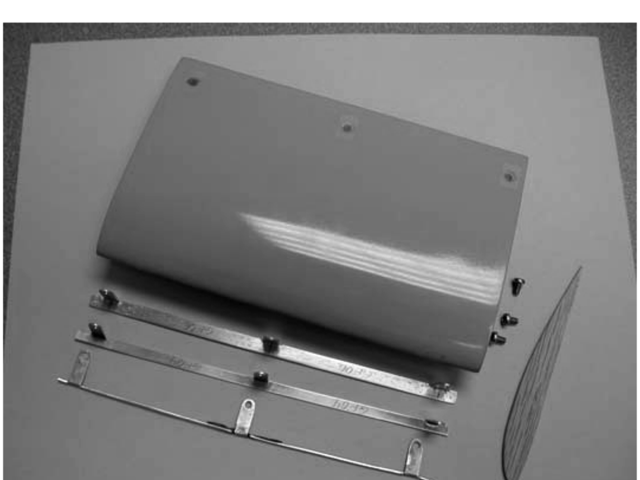

Fig. 1 Wing and Gurney flap models used in the study.

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of the wing model could be determined to within $\pm 0.25^{\circ}$. All lengths could be considered reliable to within 0.5 mm. The dynamic pressure uncertainty is estimated at ± 0.1 kPa. Finally, the lift and drag force readouts are estimated to be reliable to within ± 0.05 N.

Discussion of Results

First lift and drag measurement runs have been completed for $\alpha = 3$–15°. The standard wind tunnel corrections [17] have been applied. The lift and drag exhibited the expected behavior: the presence of a Gurney flap increased noticeably both the lift and drag, with the effects increasing with the increased flap size. The combined effects on both lift and drag are shown in Fig. 2. It can be seen from this figure that the effect of Gurney flaps on aerodynamic efficiency is detrimental for all three flaps, again with the largest flap producing the largest adverse effect.

It is also noted that the advantage of the clean configuration over the flapped ones diminishes as the lift coefficient increases. This, coupled with the fact that the lift-generating capability is significantly enhanced by the addition of the Gurney flap, suggests that the clean-wing advantage should not be taken as being absolute. If, for example, one were to extend the clean-wing curve beyond its last point, the point corresponding to an uncorrected α of 15°, by extrapolation or by adding actual test data, an intersection with the 1.5%-Gurney flap curve would soon occur signifying an apparent advantage of this flapped wing. In this regard, it seems desirable to expand the present investigation matrix to include smaller flap heights. The most important conclusion which can be made about this figure is that a relatively low drop in aerodynamic efficiency, on the order of 10%, would be incurred when a 1.5%-chord Gurney flap is employed at high lift coefficients corresponding to takeoff and landing. It is remembered that these are exactly the phases of flight during which a wake vortex hazard is most critical.

Upon completing the force measurements for each configuration, the model was instrumented for the flow visualization phase by installing the tufts as described above. Then, each configuration was tested at $\alpha = 3$–15° with one-degree increments, 5 times at each α. After lift and drag data have been retaken for comparison, the tunnel was brought to its minimum speed of approximately 4 m/s. At this speed, the distance from the wing trailing edge to the start of the outer organized vortical structure, i.e., the outer vortex "rope," x_s, in mm, was measured. Also, the number of tufts entrained in this vortex rope, N was recorded. A typical vortex rollup is shown in Fig. 3. It depicts the vortex produced by the 4%-Gurney flap configuration at $\alpha = 15^{\circ}$. Next, the vortex roll-up tightness factors have been calculated as $\mathrm{RTF} = N/x_s$. The value of the RTF at a specific α was next calculated as the simple average of the values for the five runs at that α. It is shown in [13] that RTF should be a linear function of α, increasing with vortex strength. RTF has been used in the present study to compare near-field vortex strengths.

It can be seen from Fig. 4 that the RTF values for the four configurations investigated in this study indeed exhibited near-linear behavior. To facilitate this comparison, least-square straight-line fits have been added to each data set. It is also seen that, over most of the range of α, the vortex strength, as quantified by RTF, decreases as the Gurney flap height increases. The weaker vortex in the case of a flapped configuration may be attributed to the fact that the flap inhibits the spanwise motion of the air near the wing trailing edge and thus impedes the normal roll-up process [13,14]. It is noted that this effect is not linear; the largest change in RTF occurred when the 1.5% flap was installed on the baseline wing. Also, the slopes of the RTF vs C_L lines decrease as the flap height increases. It can be seen from this figure that a drop in RTF of about 28% can be achieved by using the 1.5% Gurney flap at $\alpha = 15^{\circ}$. This percentage gain is almost a threefold of the loss in the lift-to-drag ratio at the same α as shown in Fig. 2. Based on this observation, it can be concluded that it might be advantageous to use low-height Gurney flaps as vortex alleviation devices, because the negative effect on lift-to-drag is more than compensated for by the moderating effect on vortex strength. Before this section is left, it should be noted that the RTF method has proven to be remarkably reliable. Some specific illustrations for this will be presented later.

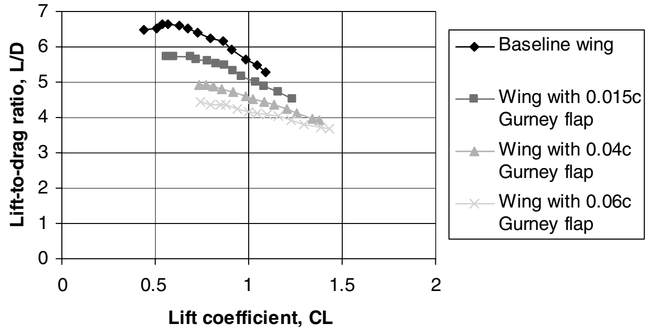

Fig. 2 Effect of Gurney flap height on lift-to-drag.

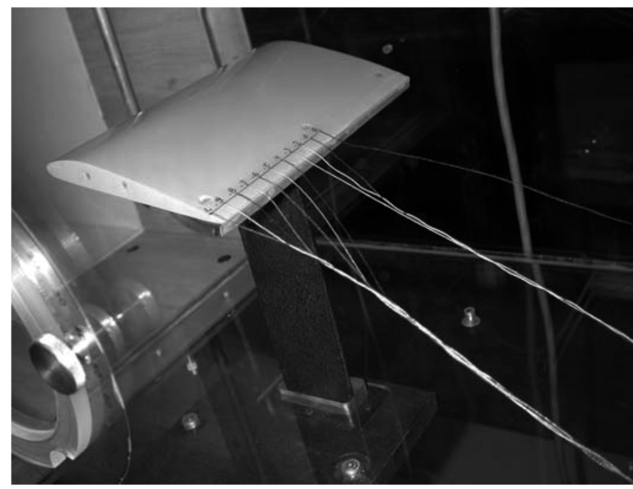

Fig. 3 Vortex rollup from wing with 0.04*c* Gurney flap, $\alpha = 15^{\circ}$.

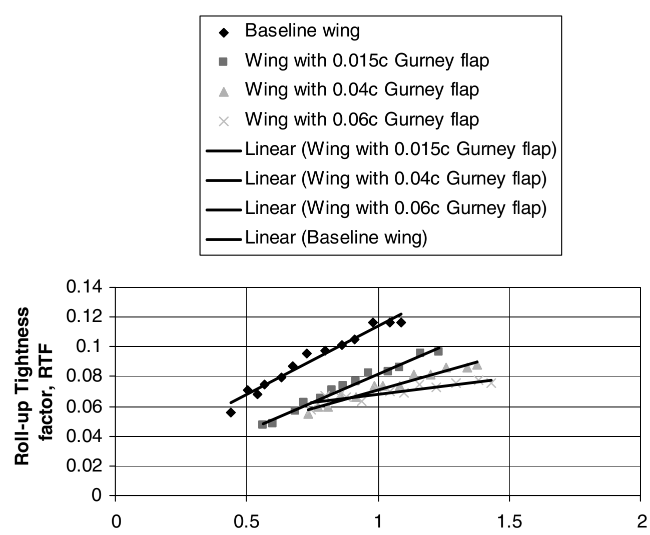

Fig. 4 Effect of Gurney flap height on roll-up tightness factor.

The effect of Gurney flap height on the wing lift-to-drag ratio at $\alpha = 15^{\circ}$, uncorrected, is shown in Fig. 5. A least-square quadratic fit has been added to the data. It is seen that the drop follows quite well the parabolic line. The effect of Gurney flap height on RTF at $\alpha = 15^{\circ}$, uncorrected, is shown in Fig. 6. This data set also closely matches a parabolic curve fit. In this study the RTF values at $\alpha = 15^{\circ}$ have been found as averages of 10 runs for each configuration. It is pointed out that these 10-point averages were found to be very close

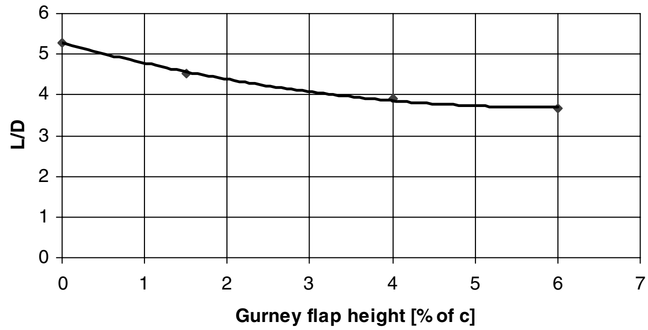

Fig. 5 Effect of Gurney flap height on lift-to-drag, $\alpha = 15°$.

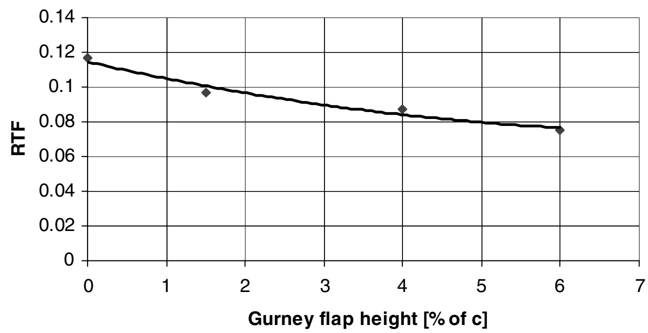

Fig. 6 Effect of Gurney flap height on roll-up tightness factor, $\alpha = 15°$.

to the usual 5-point averages which have been used to generate all points in Fig. 3 when both 10- and 5-point averages have been available. For example, the 10-point average for the configuration employing the 4% Gurney flap has been found to be 0.0833. A series of five additional runs have been carried out on a later day resulting in an average of 0.0876. Six more runs have been completed yielding one 3-point average of 0.0848 and an overall 21-point average of 0.0862. Two more individual runs, conducted on yet a different day, produced the value of 0.0875 each, thus a 23-point average of 0.0863. Based on these results, the relative errors with the 10-point average as the basis have been found to be 5.2%, 1.8%, 3.5%, and 3.6% for the 5-, 3-, 21-, and 23-point averages, respectively. These results exemplify the high reliability of the RTF method. The curves of Figs. 5 and 6 are both well behaved. As such, they indicate good levels of consistency of the experimental data discussed above.

Conclusions and Recommendations

A series of three Gurney flaps of varying height have been studied experimentally, in combination with a baseline rectangular wing model, to examine the effects of the flap height on the wing wake vortex strength and aerodynamic efficiency. Flow visualization tufts have been used to study the vortex patterns, both qualitatively and quantitatively. It has been found that the addition of the Gurney flaps markedly altered the vortex roll-up pattern, producing weaker vortices in the near-field studied, as measured by the roll-up tightness factor. This desirable effect increased with the flap height. At the same time, the addition of the flaps caused the wing's lift-to-drag ratio to decrease, although to a degree which has been much lower than the advantageous effect on vortex strength; for example, a 10% decrease in lift-to-drag vs a 28% decrease in vortex strength for a 1.5%-chord Gurney flap at a high angle of attack. It appears that noticeable vortex alleviation can be attained even with relatively low height Gurney flaps. Therefore it seems justified to investigate Gurney flaps having heights in the range 0.5–1% of the wing chord in the future. The present study clearly confirmed the usefulness of the roll-up tightness factor for quantifying vortex strengths.

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