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Technical Notes

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Gurney Flap Scaling for Optimum Lift-to-Drag Ratio

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Introduction

A GURNEY flap consists of a very small flat plate positioned perpendicular to the trailing edge on the pressure side of an airfoil. Such flaps are known to increase the lift, and for a given lift coefficient, to reduce drag under moderate- to high-lift conditions.[1–8] The primary focus of most studies so far has been on the lift enhancement capabilities of the device for both single- and multi-element airfoils. The recent report by Ashby[8] discusses important aspects of the flow physics involved and provides an extensive review of previous works. There seems to be, however, a lack of studies dedicated to the detailed investigation of the often reported low-drag increments associated with small Gurney flaps.

It is also known that the potential of a Gurney flap in maximizing the lift-to-drag ratio of airfoils is best achieved if the flap height is kept quite small. Indeed, Liebeck[1] found that the drag increased noticeably for flap heights h larger than 2% of the chord c. This observation made by Liebeck has over time been more or less accepted as the geometrical criterion for optimum Gurney flaps in the sense of maximizing the lift-to-drag ratio. It has, however, never been investigated in detail.

This Technical Note aims at providing evidence that there exists a flow-based scaling for the Gurney flap heights that yield an increase in lift-to-drag performance compared with the baseline airfoil at the same angle of attack (beneficial Gurney flaps). The results presented here, which also include data from other sources, support this statement and further suggest that the boundary-layer thickness δ, measured at the trailing edge on the pressure side of the baseline airfoil, is not only an appropriate flow-based normalization for the flap height but is also a proper order of magnitude for the flap height providing the largest increase in the lift-to-drag ratio (optimum Gurney flap). Considering the thickness δ at the Reynolds numbers and angles of attack of most applications and test conditions, it comes as no surprise then that 1 to 2% chord Gurney flaps have usually been found to be beneficial.

The choice of the boundary-layer thickness δ (as just defined) as a proper scaling for the optimum Gurney flap incorporates the combined effects of airfoil geometry, angle of attack, Reynolds number, and flow regime. The idea for this scaling was proposed earlier by the authors[7] and originated from a rather intuitive physical understanding of Gurney flaps.

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Experimental Method

A total of seven Gurney flaps were tested, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 5.0% c, on a slightly modified LA203A airfoil[7] (airfoil truncated at 97.2% c) in a closed-return low-speed wind tunnel. The freestream turbulence intensity in the test section was recorded as 0.2% for a chord Reynolds number of 2.5×10^5. Lift and drag forces as well as boundary-layer thickness measurements were performed. The wind-tunnel model had a span of 900 mm (35.4 in.) and a chord of 222 mm (8.75 in.) and was mounted vertically in the test section with a gap of 2.5 mm (0.1 in.) between the free end of the model and the ceiling of the test section.

An electromechanical balance was used to measure the lift and drag forces acting on the airfoil model. The use of a balance for drag measurements, although admittedly not ideal for two-dimensional testing, provided data that are nonetheless found to be consistent with the trends observed in other studies.[4–6] From the lift and drag results, the Gurney flap heights that were beneficial (increase in the lift-to-drag ratio) and the one that was optimum were identified for a particular angle of attack. The boundary-layer thickness at the trailing edge on the pressure side of the baseline airfoil was obtained from velocity measurements performed with a flattened pitot tube mounted on a traversing mechanism at midspan. More details about the experimental method can be found in Ref. 7.

Results and Discussion

The results presented in Fig. 1 suggest that the height of beneficial Gurney flaps scales with the boundary-layer thickness. Owing to the uncertainty in the experimental data and also to the limited number of Gurney heights tested, a single optimum for each angle of attack could not be reasonably inferred (the lift and drag data can be found in Ref. 7). Accordingly, a range of beneficial Gurney flaps, which includes the optimum, is presented. More data taken with increased accuracy and with finer increments in flap heights would be necessary to determine more precisely the actual value of the optimum in terms of δ.

It is possible, however, to test the new scaling against other available results from the literature. Figure 2 provides the heights of the most beneficial Gurney flaps tested by other investigators, over a wide range of Reynolds numbers, against rough but indicative estimates of their boundary-layer thickness at the trailing edge. Note

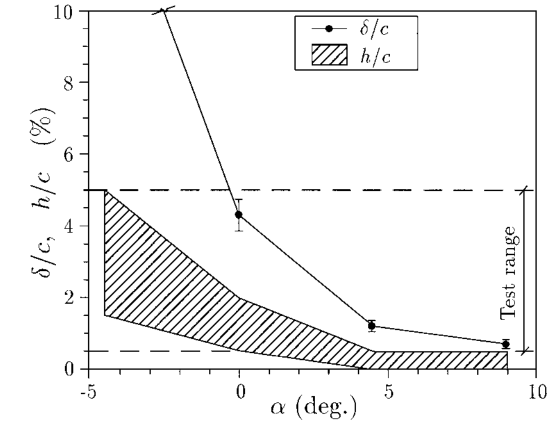

Fig. 1 Measured boundary-layer thickness δ/c and range of beneficial Gurney flap heights h/c for the LA203A airfoil as a function of angle of attack (note the dashed lines indicating the range of flap heights tested).

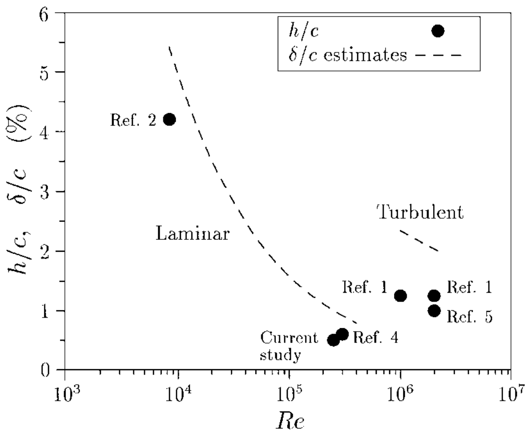

Fig. 2 Heights *h/c* of the most beneficial Gurney flaps (among those tested) by different investigators and boundary-layer thickness *δ/c* estimates for a flat plate as a function of Reynolds number.

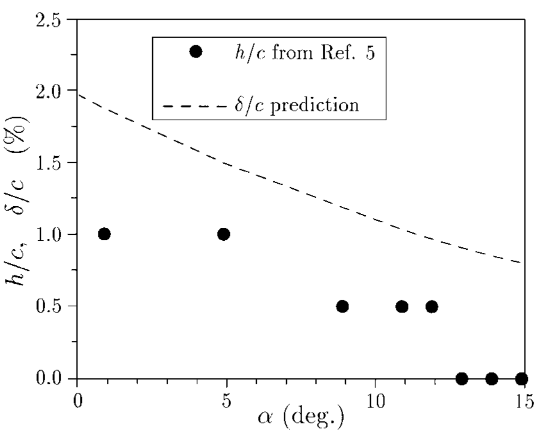

Fig. 3 Turbulent boundary-layer thickness at the airfoil trailing edge on the pressure side (computed from XFOIL predictions) and upper limit of beneficial Gurney flap heights for a NACA 4412 airfoil at *Re* = 2 × 10⁶ (as reported by Storms and Jang[5]).

that, concerning the data attributed to Neuhart and Pendergraft,[2] the 4.2% c Gurney flap was their most beneficial not in terms of optimum lift-to-drag performance but rather in terms of delaying upper surface separation because no force measurements were actually performed in that study. The δ estimates in Fig. 2 were obtained either from the simple Blasius boundary-layer results for laminar flow ($\delta/c \simeq 5Re^{-1/2}$) or by the empirical relation $\delta/c \simeq 0.38Re^{-1/5}$ for a turbulent boundary-layer on a smooth flat plate. These approximations are admittedly quite crude (boundary-layer evolutions under zero pressure gradient) but they nonetheless yield reasonable estimates short of actual measurements. Furthermore, comparing the measured data of Fig. 1 obtained at $Re = 2.5 \times 10^5$ and the prediction $\delta/c = 1\%$ (flat plate at the same Reynolds number), one may infer that such estimates are satisfactory for the present purpose and representative of moderate angles of attack (5–6 deg) and moderate lift cases. Thus, the data of Fig. 2 provide further support to the proposed scaling and do so over a wide range of Reynolds numbers in both laminar and turbulent boundary-layer regimes.

To further test the proposed scaling, the computational airfoil analysis and design code XFOIL[9] was run to obtain boundary-layer parameters for the airfoil used by Storms and Jang,[5] who tested four Gurney flap heights (0.5, 1.0, 1.5, and 2.0% c) on a NACA 4412 airfoil. Their test Reynolds number was approximately 2×10^6 with fixed transition at 2.5% c and 10% c on the suction and pressure side, respectively. These test conditions were input into XFOIL and predictions for the displacement and momentum thicknesses (δ^* and θ) at the trailing edge on the pressure side were obtained for their baseline NACA 4412 airfoil at several angles of attack. For each angle, a boundary-layer thickness was calculated assuming the usual $1/n$-power-law velocity profile: $\delta = [(H+1)/(H-1)]\delta^*$, where $H \equiv \delta^*/\theta$. The upper limit of the range of beneficial Gurney flap sizes tested by Storms and Jang[5] is shown on Fig. 3 against the angle of attack. These data, thus, represent the longest flaps still providing an increase in the lift-to-drag ratio as compared with the performance of the baseline airfoil. Again, these results strongly support the proposed flow-based scaling for beneficial Gurney flaps. Note the similarity in the general trends of Figs. 1 and 3.

Further support is also provided by the results of Vijgen et al.,[3] who tested a 1.5% c serrated Gurney flap on a full-span wing model. They estimated the boundary-layer thickness at the trailing edge on the pressure side of their wing using a two-dimensional integral boundary-layer method. Their results indicate that the 1.5% c serrated Gurney flap, which did provide an increase in lift-to-drag ratio for most of the lift range considered, was indeed submerged in the boundary layer.

Thus, it appears that the proposed scaling is well supported by a wide range of results from different investigators. Although the data of Figs. 2 and 3 are approximate and must be taken as indicative rather than definitive, it can be concluded that beneficial Gurney flaps, in terms of increasing the lift-to-drag ratio of an airfoil, are found to have a height never greater than the local baseline boundary-layer thickness. This statement should be viewed, however, as a necessary but not necessarily sufficient condition for the beneficial use of Gurney flaps. Indeed, in practice, the benefit of Gurney flaps must be established at given lift conditions rather than at given angles of attack. The recent results obtained by Myose et al.[10,11] on a NACA 0011 airfoil as well as our own data[7] emphasize that distinction. Further work toward a more practical criterion for beneficial Gurney flaps is still required.

From a fundamental perspective, the fact that beneficial Gurney flaps must be small enough to be submerged in the high-sheared flow of the pressure-side boundary layer appears as a crucial element in the understanding of the low drag associated with the device. This is especially the case when there is no significant flow separation on the suction side of the baseline airfoil. One may speculate that viscous effects are somehow important in the Gurney physics, perhaps as the stabilizing agent by which an attached stationary bubble may indeed exist right behind the flap, as first hypothesized by Liebeck[1] and qualitatively supported by Neuhart and Pendergraft.[2] This attached bubble may act as a fluid extension of the airfoil providing an off-the-surface pressure recovery and, thus, a higher base pressure behind the flap. In addition, the bubble may also be involved with some compression effect acting on the two vorticity layers forming the near wake. Those aspects of the Gurney flap physics remain open questions.

Conclusion

This Technical Note has provided evidence that there is a flow-based scaling for the size of the optimum Gurney flap for best lift-to-drag performance. This result appears intrinsically connected with the physics of this type of flap. Consequently, a purely geometric criterion based solely on the chord of the airfoil may be misleading in determining the size of a beneficial Gurney flap. A proper scaling parameter has been shown to be the boundary-layer thickness at the trailing edge on the pressure side of the baseline airfoil. This simple, yet fundamental scaling is well supported not only by the present experimental results, but also by a wide range of data by other investigators. For beneficial and optimal Gurney flap performance, it thus turns out to be most important that the flap be submerged within the local boundary layer.

Acknowledgments

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References

[1] Liebeck, R. H., "Design of Subsonic Airfoils for High Lift," *Journal of Aircraft*, Vol. 15, No. 9, 1978, pp. 547–561.

[2] Neuhart, D. H., and Pendergraft, O. C., "A Water Tunnel Study of Gurney Flaps," NASA TM 4071, Nov. 1988.

[3] Vijgen, P. M. H. W., van Dam, C. P., Holmes, B. J., and Howard, F. G., "Wind-Tunnel Investigations of Wings with Serrated Sharp Trailing Edges,"

Low Reynolds Number Aerodynamics, edited by T. J. Mueller, Vol. 54, Lecture Notes in Engineering, Springer–Verlag, New York, 1989, pp. 295–313.
[4]Selig, M. S., Donovan, J. F., and Fraser, D. B., *Airfoils at Low Speeds*, SoarTech 8, SoarTech Publication, Virginia Beach, VA, 1989, pp. 73–75.
[5]Storms, B. L., and Jang, C. S., "Lift Enhancement of an Airfoil Using a Gurney Flap and Vortex Generators," AIAA Paper 93-0647, Jan. 1993.
[6]Jang, C. S., Ross, J. C., and Cummings, R. M., "Computational Evaluation of an Airfoil with a Gurney Flap," AIAA Paper 92-2708, June 1993.
[7]Giguère, P., Lemay, J., and Dumas, G., "Gurney Flap Effects and Scaling for Low-Speed Airfoils," AIAA Paper 95-1881, June 1995.
[8]Ashby, D., "Experimental and Computational Investigation of Lift-Enhancing Tabs on a Multi-Element Airfoil," NASA TM 110432, Dec. 1996.
[9]Drela, M., "XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils," *Low Reynolds Number Aerodynamics*, edited by T. J. Mueller, Vol. 54, Lecture Notes in Engineering, Springer–Verlag, New York, 1989, pp. 1–12.
[10]Myose, R., Heron, I., and Papadakis, M., "Effect of Gurney Flaps on a NACA 0011 Airfoil," AIAA Paper 96-0059, Jan. 1996.
[11]Myose, R., Papadakis, M., and Heron, I., "A Parametric Study of the Effect of Gurney Flaps," AIAA Paper 97-0034, Jan. 1997.

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Studies on Alleviation of Buffet in Periodic Transonic Flow

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Introduction

AIRCRAFT in flight can be subject to buffet excitation, due to large flow unsteadiness associated with boundary-layer separation or, as in the case of transonic flows, with periodic self-excited shock-induced oscillations. Buffet can also occur in cavities such as aircraft bomb bays, exhaust diffuser of steam turbines, turbomachinery blades, and supersonic intakes of aeroengines. Buffeting is defined as the structural response to pressure excitations. In the case of an aircraft, buffeting can lead to structural deformations and failure of primary, for example, wings and tail plane, and secondary, for example, flaps and rudder, structures. Buffeting can also cause both discomfort to passengers and difficulty for the pilot in attempting to control the aircraft. Thus, buffet limits the cruising speed of commercial aircraft and severely degrades the maneuverability limits for a combat aircraft. An understanding of buffet on oscillatory wings with control surfaces is of specific concern in aeroelastic investigations in determining the power requirements in active control systems for load alleviation and flutter control.

There have been several studies, computational and experimental, on transonic periodic flow over an 18% thick biconvex airfoil.[1–8] The general understanding of this type of flow is as follows: 1) the periodic motion on an airfoil is sustained by the communication across the trailing edge, and the frequency of the periodic motion is directly related to the time required for the signals to travel over the chord length; 2) the periodic motion takes place over a narrow range of Mach numbers; and 3) shock waves move in antiphase on the upper and lower surfaces during shock oscillations.

The known means of eliminating or suppressing shock motion (see, for example, Refs. 3 and 4) include 1) buffet breathers, 2) spanwise wires, 3) altered trailing edge, 4) passive control, 5) vortex generators, and 6) reduced stiffness and span. A spanwise strip located aft of the shock wave eliminated high-frequency transonic oscillations but increased subsonic low-frequency buffet. A suitably positioned vortex generator can also produce a similar effect. Passive control with porous surfaces and buffet breather also have been found to suppress shock oscillations in the transonic range.

This Note presents some of the results of a transonic computational fluid dynamics (CFD) study performed on a biconvex airfoil with a splitter plate extension or with surface cooling with a view to suppress the periodic motion.

CFD Code Development and Validation

A two-dimensional, thin-layer Navier–Stokes code with a moving grid was developed for these investigations. The relative merits of various methods for prediction of transonic periodic flows has been discussed by Edwards.[6] The code developed for the present investigations also has a moving grid option to investigate the effect on periodic flow of a trailing splitter plate motion, a flap motion, and a pitching airfoil.

The implicit code solves the mass-weighted, thin-layer Navier–Stokes equations using an upwind implicit predictor/corrector cell-centered finite volume scheme. A modified version of the simple algebraic Baldwin–Lomax turbulence model is employed. Sutherland's law was used for viscosity, and the Prandtl analogy was employed for thermal conductivity.

A C grid was generated with a 1% radius at the leading edge of the airfoil to remove computational difficulties. The minimum normal grid spacing was reduced to 5×10^{-6} chords, ensuring a value of $y^+ < 5$ everywhere on the airfoil surface. Transition to turbulence was fixed on both the upper and lower surface at 3% chord. The solution was again started from rest on a coarse grid, where 50 iterations were performed before transferring to the fine grid.

The test cases used for validation of periodic flows were 1) 18%-thick circular arc airfoil at zero incidence, Mach number of 0.771, and Reynolds number of 11×10^6; and 2) NACA0012 airfoil at 6-deg incidence, Mach number of 0.7, and Reynolds number of 10×10^6. These test conditions lie within the unsteady range found experimentally and computationally.

The validation for periodic transonic flow over an 18%-thick biconvex airfoil is shown in Fig. 1. The predicted reduced frequency is 0.44. The change in lift coefficient is 0.247. This compares with the corresponding predicted values of 0.465 and 0.265 of Ref. 6 and 0.41 and 0.23 of Ref. 9.

The code correctly predicted Tijdeman type B shock motion on a rigid NACA0012 airfoil at $M_\infty = 0.7$, $Re_\infty = 10 \times 10^6$, and incidence of 6 deg. This type of periodic motion has been computed by Edwards.[6] The nondimensional frequency predicted is 0.21, compared with 0.235 by Edwards.

Some investigations were conducted on the effect of flap deployment. The effect of a flap deployment by a small angle of 3 deg during a time period 1/16 of a period of the original periodic motion (which is considerably less than the time required for the signals to go around the airfoil in one cycle) resulted in the change in shock motion from type B to type A, indicating the significant effect of the trailing edge on periodic transonic flow.

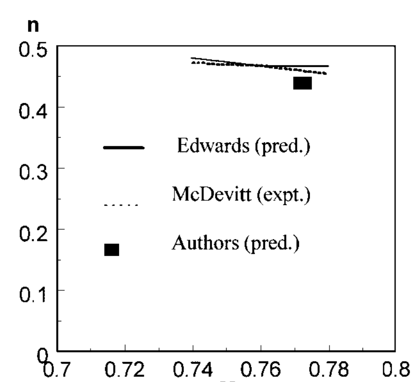

Fig. 1 Correlation of reduced frequencies for periodic transonic flow over an 18% thick airfoil; $M_\infty = 0.77, Re_\infty = 11 \times 10^6, \alpha = 0$.

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