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Technical Notes

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Experimental Aerodynamics of Mesoscale Trailing-Edge Actuators

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Introduction

CONTROL of aeroelastic instabilities is a significant issue for all aircraft, but it is particularly critical for long-duration unmanned air vehicles with high-aspect-ratio wings. Existing control methods are most effective for low frequencies and low-order elastic modes, which are not suitable for these types of aircraft.[1] A higher-bandwidth approach is needed, and small actuators distributed across the span offer the potential of high temporal and spatial bandwidth.

Previous research[2–4] has indicated that a "Gurney flap" can significantly alter the lift and pitching moment of a wing. This device consists of a small trailing-edge flap with a height on the order of 1% of the airfoil chord oriented at a right angle to the pressure surface. In this configuration the lift is enhanced with either a small drag penalty[2] or a slight drag reduction.[3] The lift increment for partial-span Gurney flaps is approximately proportional to the flap span.[4] Dividing the Gurney flap into individually controlled miniature trailing-edge effectors (MiTEs) might permit variation of the spanwise loads distribution, allowing active damping of the aeroelastic vibrations. Because of the small size and great number of actuators, this solution would have advantages of simplicity, high bandwidth, great pattern variety, and redundancy.

There are still issues to resolve regarding the utility of segmented Gurney flaps in an aeroelastic control scheme. First, these devices have much smaller aspect ratios than those examined by Myose et al.,[4] and so their potential for altering the loads must be verified. Second, the spacing between the flaps could affect the response, as suggested by Yen-Nakafuji et al.[5] Third, there is no information available regarding the spanwise distribution of loads for a small flap. To develop a proper control system, it is necessary to understand how a single MiTE affects the aerodynamic forces along the entire wing span.

This work is part of a larger study that includes the development of high-frequency MiTE actuators, computational and experimental measurements of the steady-state and transient response of an airfoil to flap actuation, and the implementation of a control system on a simple flexible wing. This Note discusses the measured load response of a wing at moderate Reynolds number as a result of a set of 16 MiTEs.

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Experimental Apparatus

The MiTE experiments are conducted in the Stanford Flow Control Wind Tunnel, a subsonic (0–22-m/s) closed-loop tunnel with excellent flow uniformity and freestream turbulence below 0.5%. The test section is 61 cm wide by 91 cm high by 4 m long.

The untwisted, rectangular airfoil model has a MESO5 profile, and it is mounted vertically in the test section (Fig. 1a) between two AMTI MC3A-6 force-and-moment balances. The wing has a span of 86.9 cm and has end plates to ensure two-dimensionality across the midspan region. The design chord length for the airfoil is 61.0 cm, but 3.3 cm were trimmed from its trailing edge to provide a 6-mm-thick blunt base for MiTE attachment. A flap manifold extends 2.5 cm from this blunted surface, so that the actual airfoil chord is $c = 60.2$ cm. A boundary-layer trip is installed at a position 12.6% of the chord downstream of the leading edge on both the pressure and suction surfaces.

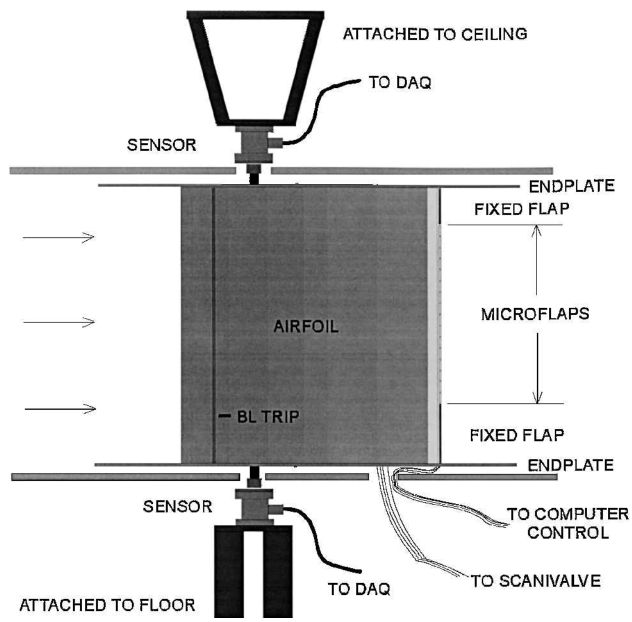

Fig. 1a Experimental apparatus: wind-tunnel experiment.

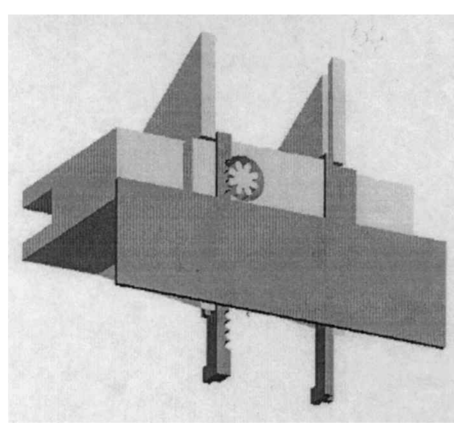

Fig. 1b Experimental apparatus: MiTE actuator.

Sixteen MiTEs are attached to the blunt trailing edge around the spanwise midpoint. Each MiTE is a 1-mm-thick by 1-cm-high by 3-cm-wide plate that moves along a track normal to the pressure surface, as shown in Fig. 1b. (The MiTEs were designed and built by B. Park, and they are described fully in Ref. 6.) This height results in an extension of 1.6% of the chord from the surface. The device is actuated by a small dc motor that can oscillate the plate in excess of 15 Hz. The flaps move between two positions: fully up or fully down. A third "neutral" position was tested by turning off the actuator and fixing the flap in a centered location. There are 1.5-mm gaps between adjacent flaps. Each track requires a triangular support that protrudes 10 mm above the wing surface on each side, leading to a small drag penalty. Future MiTEs should eliminate or reduce the size of these tracks and their supports. The 16 functional flaps occupy only the central 48 cm of the wing span, and so fixed flaps of the same height were mounted over the remainder of the span to simulate a full-span Gurney flap.

The responses from the two force and moment balances were superposed to determine the total load within an accuracy of $\Delta C_L = \pm 0.009$, $\Delta C_D = \pm 0.007$, and $\Delta C_M = \pm 0.0011$ for full-span flap tests. Because this drag uncertainty is about as large as the expected drag increments, they are not reported here. Drag measurements using the wake-momentum balance technique are reported in Ref. 7. Partial span tests had a higher accuracy, with the relevant uncertainties reduced to $\Delta C_L = \pm 0.0047$ and $\Delta C_M = \pm 0.0008$. All data were corrected for wall interference effects. Because these effects are significant, they add an additional bias uncertainty (<2%) for the absolute loads magnitudes. However, this Note focuses on the relative changes caused by these actuators, and so the bias does not affect the discussion here.

Pressure taps were drilled near the wing's midspan location, allowing streamwise pressure profiles at that position. The pressures were sampled with a Scanivalve switching system and a single Validyne DP45-14 transducer, which has an uncertainty of $\Delta C_p = \pm 1.7\%$. The profiles were integrated to determine the section lift coefficient, whose uncertainty is $\Delta C_l = \pm 0.0020$. No taps could be located inside the flap manifold, and so the pressures at the trailing edge were not known. Thus, the absolute C_l might be up to 2% different from the integrated values, although the relative load changes are not greatly affected. The section lift was corrected for wall-interference effects, but the pressure profiles do not include streamline curvature corrections.

Results

Initial tests were conducted to verify the full-span Gurney flap response. The loads were measured with the wing in three full-span conditions: the neutral, down, and up positions. The lift vs angle of attack for $Re_c = 7.5 \times 10^5$ ($U_\infty = 18.8$ m/s) is shown in Fig. 2a. At low to moderate angles of attack, C_L increases by 0.24 between the neutral and down positions, while it decreases by 0.23 between neutral and up. For the down position the lift increment decreases slightly at high angles of attack, but there is still an increase in $C_{L,\max}$. The up position becomes less effective at high angles as well, having no effect beyond stall. The nose-down pitching moment (not shown) also changes when the flaps are actuated, with C_M decreasing by 0.06 between the neutral and down positions for low to moderate angles of attack. C_M rises by the same amount when the flaps are in the up position. Nearly identical loads responses were observed for all Reynolds numbers above 2×10^5. A second set of tests was conducted with the gaps between functional flaps sealed with tape, with no measurable change in the loads seen.

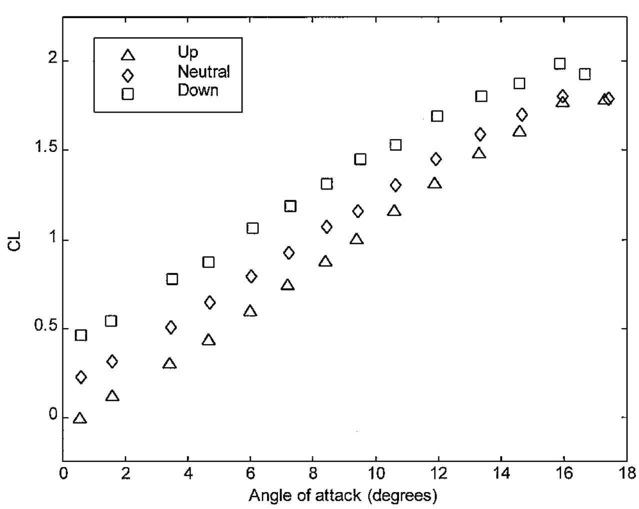

Fig. 2a Full-span flap response: lift curves.

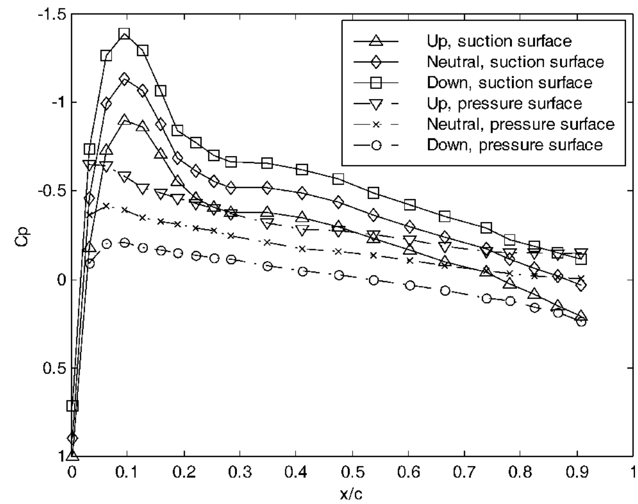

Fig. 2b Full-span flap response: pressure profiles at midspan at $\alpha = 0.40$ deg.

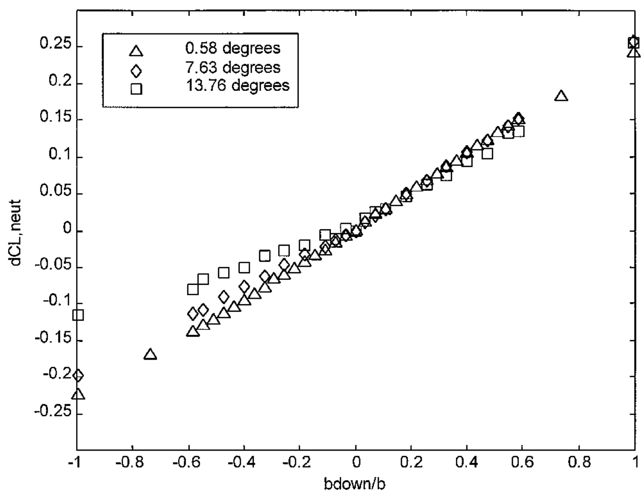

Fig. 3 Change in lift relative to neutral position for partial-span flaps.

The pressure profiles for the full-span flap conditions were also measured. The streamwise profiles at midspan are shown in Fig. 2b. Because of the transducer limitations, these tests were performed at $Re_c = 5.3 \times 10^5$. The basic response is comparable to earlier Gurney flap experiments,[2] with a shift in the curves all along the wing. Integrating these profiles, the change in C_l relative to the neutral case is +0.23 when down and −0.21 when up, giving values close to those measured by the balances.

Partial-span tests were conducted at $Re_c = 9.1 \times 10^5$ to improve the measurement resolution. Figure 3 displays the change in C_L relative to the neutral position vs b_{down}/b, the fraction of the trailing edge in the down position. Here, $b_{\mathrm{down}}/b = -1$, 0, and 1 in the up, neutral, and down positions, respectively. Near 0 deg the response is approximately linear, with only slight deviation near $b_{\mathrm{down}}/b = \pm 1$, when the end of the flap is near the end plates. At higher angles the effect remains quite linear, although the slope changes at the origin, where the flaps switch from up to down. This is because the up position is less effective than the down position at higher

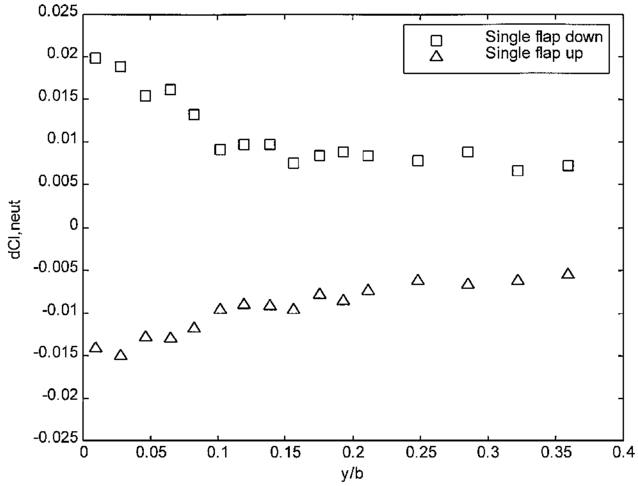

Fig. 4 Streamwise pressure profiles at midspan for single flaps at $\alpha = 0.40$ deg.

incidences, as shown in Fig. 2a. The pitching-moment trends are the same as those observed for the lift.

Because of this linear response with flap span, the superposition of flap effects was examined. Near 0-deg incidence the loads were measured in a great variety of flap configurations, including situations where actuated flaps were nonadjacent. The lift response vs b_{down}/b was identical to Fig. 3, regardless of the whether the actuators were adjacent or not, demonstrating that responses can be superposed.

The effects of single flaps were examined, with MiTEs applied at various spanwise positions. The loads response was independent of actuator position, as the measured lift and pitching moment changed by the same amount (within measurement uncertainty) for all flap locations. The midspan pressure profiles were used to determine how the loads varied with the position of the actuated MiTE. Figure 4 shows the midspan C_l relative to the neutral position as a function of the actuated flap location. As expected, the strongest effects are found when the actuated flap is aligned with the row of pressure taps. However, as the applied flap grows more distant, the response does not decay to zero, showing an influence as much as 10 flap spans away.

Conclusions

The loads response of miniature trailing-edge flaps has been studied over a variety of static conditions. Full-span tests indicate that the airfoil lift and pitching moment at a given angle of attack can be considerably altered, which implies that MiTEs are capable of the significant loads changes necessary for control. The small gaps between MiTEs (5% of the actuator span) cause no notable performance degradation. Partial-span tests about midspan show a linear response with changes in flap span, a result that should simplify control design. The load responses can also be superposed, even if the actuators are not adjacent to each other. Finally, single flaps exhibit a spanwise influence at least 10 flap spans away, demonstrating a considerable nonlocal effect. This could be an issue with designing a control system, as the MiTE concept was devised in the hopes that each flap could influence the loads at a particular section. Although the strongest effects are directly at the flap, they are clearly not limited to a small spanwise region. Overall, these experiments have shown that MiTEs are good candidates for the development of a system for damping active aeroelastic instabilities.

Acknowledgments

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Effect of the Initial Conditions on Turbulent Boundary Layers

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I. Introduction

THERE have been a number of recent developments of great interest in turbulent boundary layers. First, Castillo[1] and Castillo and George[2] analyzed the Reynolds-averaged Navier–Stokes (RANS) equations using equilibrium similarity analysis. They showed that the mean velocity profiles could be Reynolds-number invariant in the limit of infinite Reynolds number only if in the same limit the outer velocity scale were proportional to the freestream velocity U_∞. The mean deficit profile according to the analysis by George and Castillo[3] for zero pressure gradient (ZPG) and the similarity analysis of Castillo and George[2] for pressure gradient (PG) then should scale with U_∞ and is given by

$$(U_\infty - U)/U_\infty = f_{\mathrm{op}}(\bar{y}, \delta^+, \Lambda, *) \tag{1}$$

The arguments inside the similarity function f_{op}, are the outer similarity coordinate $\bar{y} = y/\delta_{99}$, the Reynolds-number dependence $\delta^+ = \delta u_*/\nu$, the pressure gradient parameter Λ, and any possible dependence on the upstream conditions $*$, respectively. The pressure gradient parameter Λ was determined via similarity analysis using the RANS equations and is given by

$$\Lambda \equiv -\frac{\delta}{U_\infty \, \mathrm{d}\delta/\mathrm{d}x}\frac{\mathrm{d}U_\infty}{\mathrm{d}x} = \text{constant} \tag{2}$$

In the limit as $Re \to \infty$, Eq. (1) is independent of the Reynolds number. However, at finite Reynolds number the function f_{op} depends on both the upstream conditions and the local Reynolds number. Moreover, George and Castillo[3] were not able to completely collapse the data with just U_∞ for ZPG boundary layers and attributed this failure to the local Reynolds-number effects. Second, Zagarola and Smits[4] found an empirical velocity scale $U_\infty\delta_*/\delta$ that did successfully collapse the data for the outer flow ($\bar{y} \geq 0.1$) of ZPG turbulent boundary

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