JOURNAL OF AIRCRAFT
Vol. 45, No. 1, January–February 2008

Engineering Notes

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Low Reynolds Number Aerodynamics of Leading-Edge Flaps

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DOI: 10.2514/1.33001

Introduction

RECENT efforts to develop micro air vehicles (MAVs) have renewed interest in low Reynolds number aerodynamics [1,2]. MAVs must be capable of executing precision maneuvers requiring high-lift coefficients at low flight speeds and high angles of attack. Laminar separation bubbles, formed when a laminar boundary layer separates, transitions, and reattaches along the airfoil chord, are prevalent in this flight regime and can limit airfoil performance. These separation bubbles can be controlled by installing turbulators on the wing to trip the boundary layer and thus delay separation [3,4]. As the Reynolds number decreases, it becomes more difficult to trip the boundary layer with surface-mounted turbulators, but significant lift improvements have been observed at Reynolds numbers as low as 2.0×10^4 when a wire is placed ahead of the leading edge [5].

It has been suggested that leading-edge devices on bird wings can eliminate laminar separation bubbles [6,7]. A protruding flap of feathers has been observed to automatically deploy both during landing maneuvers when the wing is rapidly pitching up near deep stall and during cruising flight when the wing is at a more modest angle of attack. Figure 1 shows this leading-edge flap and a suggested mechanism for deployment. High-speed video has shown that, although the leading-edge flap can deploy in segments, it ultimately spans most of the wing [8]. Thus, in cruising flight, the leading-edge flap is essentially a two-dimensional device.

The objectives of the current study are to evaluate the benefits of a leading-edge flap as a high-lift device for MAVs and offer an explanation of the aerodynamic mechanisms which result in high lift. The effects of leading-edge flaps and wires on a low Reynolds number airfoil are compared with those of surface-mounted trips. Experiments were performed at Reynolds numbers of 4.0×10^4, 7.0×10^4, 9.5×10^4, and 1.2×10^5 to represent the flight regime of large birds and MAVs.

Received 22 June 2007; revision received 6 September 2007; accepted for publication 11 September 2007.

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Experimental Setup

Apparatus and Methods

Experiments were performed in the University of Cambridge Engineering Department 1B low-speed wind tunnel. The 1B is an open-return tunnel capable of speeds up to 25 ms^{-1} with a 0.715×0.510 m working section. Turbulence intensity was measured using a hot-wire anemometry system and was found to be 0.10% between 10 and 20 ms^{-1}.

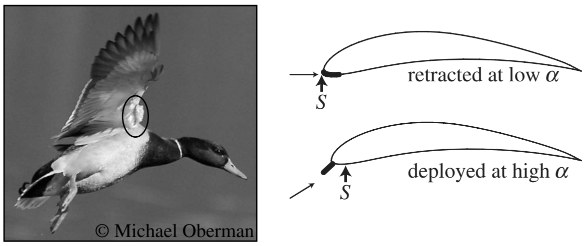
An Eppler E423 airfoil, a highly cambered low Reynolds number airfoil appropriate for MAVs and very similar to a cross section of a seagull wing [9], was used for all of the experiments described here. A wing with a chord length of 9.73 cm and a span of 71.0 cm was sting-mounted on an external Flow Dynamics Ltd. 50 N lift–drag strain gauge balance. Lift, drag, and power input to the balance were recorded at 100 Hz by a Microlink 3000 data acquisition system and time averaged over 1 s. Force measurements were supplemented by surface oil flow visualization, performed using a mixture of kerosene, titanium dioxide, and oleic acid. Wind-tunnel speed was measured using a pitot-static tube positioned upstream of the model and connected to a methylated spirits manometer. Each airfoil configuration was tested at chord Reynolds numbers between 4.0×10^4 and 1.2×10^5 for $0 \leq \alpha \leq 30$ deg in 1 deg increments.

Uncertainty and Corrections

The focus of this work is to identify the changes in flow behavior and aerodynamic mechanisms by which leading-edge flaps augment lift at low Reynolds numbers, not to provide a quantitative catalog of lift and drag data. The shapes of the lift-to-drag polars are of primary interest rather than the numerical values. Sources of experimental error were identified as flow speed, angle of attack, bias error introduced during force balance calibration, and sampling precision. The primary source of uncertainty for the clean wing is the angle of attack setting, accurate to within 0.4 deg. The total error in force coefficient measurements on the clean wing was found to be 3%. Errors associated with the installation of leading-edge flaps or wires are 4% for length, 5% for placement, and 4% for deployment angle. Because of these variations, the force coefficients for these configurations have an uncertainty closer to 8%. Error bars are omitted from the plots contained herein for clarity.

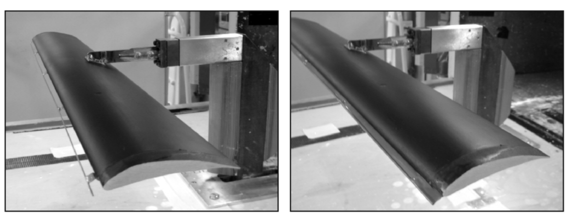
Turbulators

The avian leading-edge flap was modeled by the two devices shown in Fig. 2: a leading-edge wire and a leading-edge flap. A 1.1-mm-diam full-span wire was mounted 5 mm ahead of the leading edge of the wing on five brackets. To form the leading-edge flap, the gap between the wire and the wing was covered with tape to form an airtight flap. The flap position on the leading edge of the wing was defined by a placement angle θ and deployment angle γ with respect to the chord line as shown in Fig. 2c. To determine these angles, a photograph was taken of the wing with the leading-edge device installed and the angles were measured to within ± 2 deg using digital imaging software. For all leading-edge flap and wire tests, the flap placement angle θ was 57 deg. Both devices were tested for flap deployment angles γ of 11, 43, and 75 deg. Surface-mounted wire turbulators were installed at 2 and 5% chord by epoxying a 1.1-mm-diam wire along the entire wingspan. For configurations with a leading-edge flap, force coefficients were calculated using an

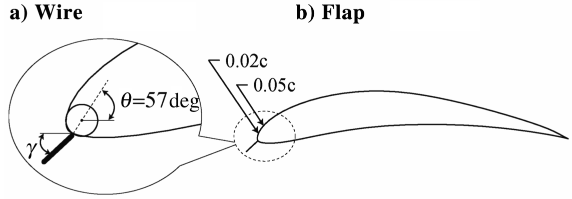


a) Mallard landing **b) Idealized leading-edge flap**

Fig. 1 Automatically deploying leading-edge flap. Above some angle of attack, the stagnation point S moves aft of the flap causing the flap to deploy passively [8].



a) Wire **b) Flap**



c) Turbulator placement

Fig. 2 Leading-edge device installation.

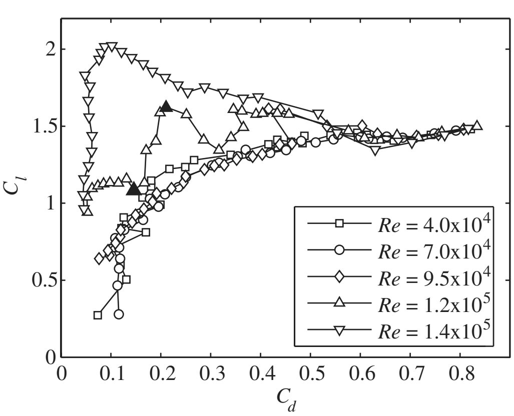
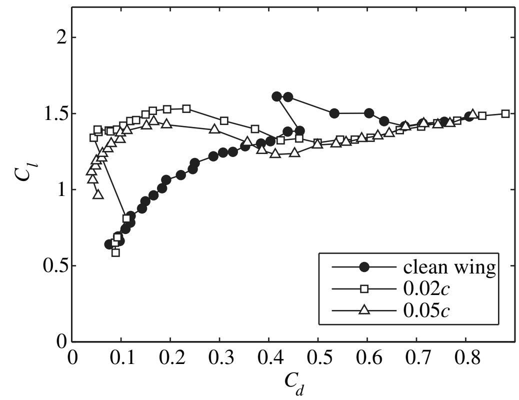
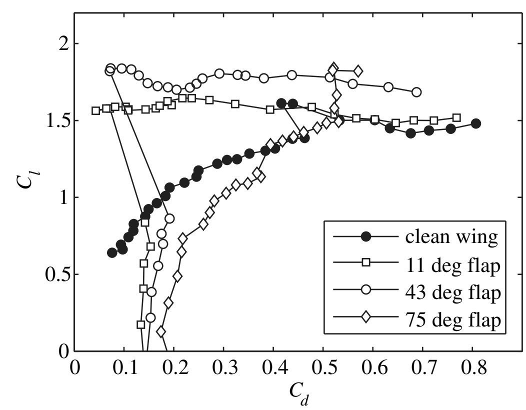


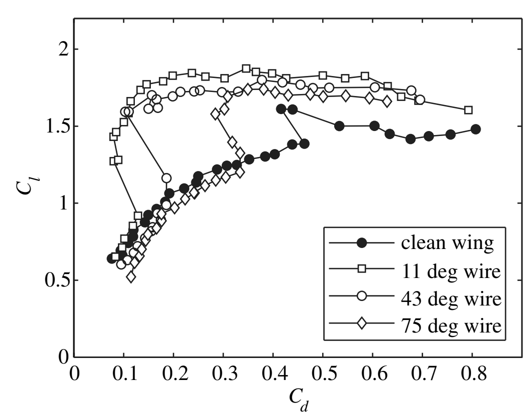
Fig. 3 Lift-to-drag polars for a clean E423 airfoil. Shaded data points are $\alpha = 8$, 13 deg.



a) Surface-mounted wire trip



b) Leading-edge flap



c) Leading-edge wire

Fig. 4 Drag polars at $Re = 9.5 \times 10^4$.

adjusted chord value accounting for the flap chord. Angles of attack, however, were defined with respect to the clean airfoil chord line regardless of airfoil configuration.

Results and Discussion

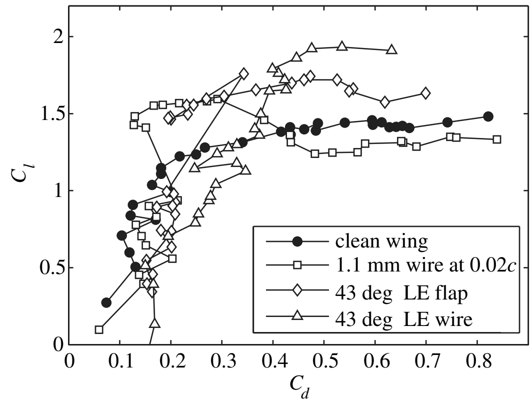
Clean Airfoil

The laminar separation bubble is the dominant flow feature for the Reynolds numbers tested here and the development of this bubble has a huge impact on airfoil performance. At relatively high Reynolds numbers, the separated laminar boundary layer transitions and eventually reattaches downstream, forming a separation bubble. At lower Reynolds numbers, the boundary layer does not transition quickly enough to reattach. The flow remains separated and a large region of recirculating flow forms at the trailing edge. In either case, the flow structure is unsteady and very sensitive to perturbations in the freestream. Separation and reattachment points can move along the chord in response to these changes.

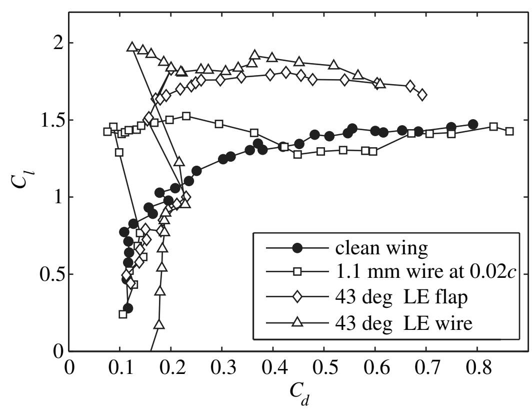
Drag polars for a clean E423 airfoil are given in Fig. 3. The airfoil performs well at $Re = 1.4 \times 10^5$, reaching a maximum C_l value over 2.0 despite the presence of a laminar separation bubble. As the Reynolds number decreases, performance deteriorates.

At $Re = 1.2 \times 10^5$, the laminar separation bubble has a much greater effect on the flow over the upper surface. As the angle of attack increases to 8 deg, the separation bubble grows and lift is low. At $\alpha = 13$ deg, the separation bubble has moved upstream and shortened, improving lift. As the angle of attack increases further, the separation bubble continues to vary in size, causing C_l values to fluctuate according to the current state of the bubble.

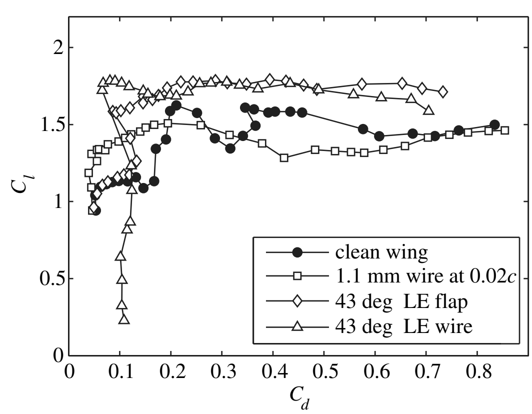
Below $Re = 1.2 \times 10^5$, the laminar boundary layer separates soon after the leading edge and is unable to reattach. Flow over the airfoil is largely separated, even at low angles of attack. As the angle of



a) $Re = 4.0 \times 10^4$

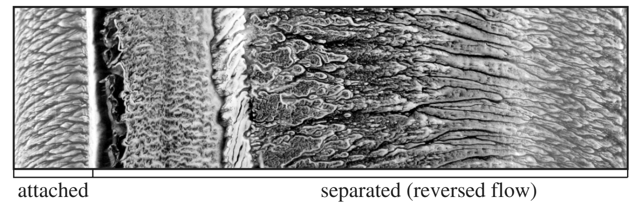


b) $Re = 7.0 \times 10^4$

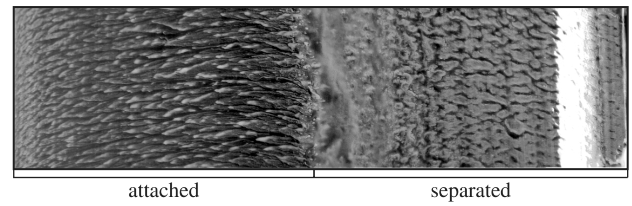


c) $Re = 1.2 \times 10^5$

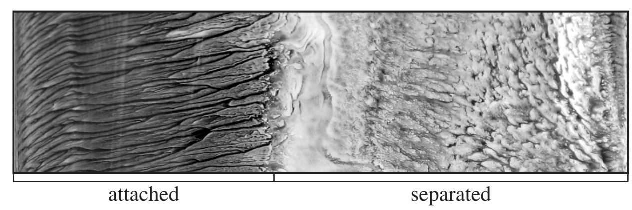
Fig. 5 Drag polars for airfoil with surface-mounted wire trip, leading-edge flap, or leading-edge wire.



a) Clean wing: $C_l = 1.1$, $C_d = 0.3$



b) Leading-edge wire: $C_l = 1.6$, $C_d = 0.1$



c) Leading-edge flap: $C_l = 1.8$, $C_d = 0.1$

Fig. 6 Surface oil flow visualization for $Re = 9.5 \times 10^4$, $\alpha = 12$ deg. Flow is from left to right.

attack increases, the separation point moves upstream but the flow does not reattach and lift remains relatively low, leveling off near $C_l = 1.5$.

Surface-Mounted Wire Trip

Surface-mounted wire trips were found to improve lift for low to mid angles of attack but were ineffective at high angles of attack (Fig. 4a). Drag polars for these turbulators are characterized by a smooth rise in C_l with angle of attack before smoothly dropping down to clean wing values. Chordwise position is not critical, but maximum lift values are achieved at the 2% chord position. Although the trends are similar at all of the Reynolds numbers tested, the largest lift improvements occurred at the lowest Reynolds numbers. Lift coefficients at $Re = 4.0 \times 10^4$ and 7.0×10^4 increased from 1.3 to 1.6 and 1.2 to 1.5 at $\alpha = 13$ deg for the wire placed at 2% chord.

Leading-Edge Devices

Drag polars for the wing fitted with the leading-edge flap and wire are given in Figs. 4b and 4c. These plots are characterized by a sharp increase in C_l at some critical angle of attack. At lower angles of attack with a leading-edge flap, lift is lower and drag is higher than that of the clean airfoil, but once this angle of attack has been reached, airfoil performance improves dramatically and the high C_l values are relatively constant for all higher α. Steeper deployment angles delay the effectiveness of both leading-edge devices to higher angles of attack.

Drag polars with the leading-edge wire installed (Fig. 4c) are very similar to those with the leading-edge flap. Again high lift at high angles of attack can be achieved even at the lowest Reynolds number. Like the flap, the wire inhibits airfoil performance at low angles of attack but to a lesser degree. The maximum lift coefficient for the leading-edge wire is slightly lower than the flap, 1.9 for $\gamma = 11$ deg, $\alpha = 20$ deg at $Re = 9.5 \times 10^4$.

Figure 5 compares the drag polars of the 2% chord surface-mounted wire, 43 deg leading-edge flap, and 43 deg leading-edge wire for various Reynolds numbers. At $Re = 4.0 \times 10^4$, the $\gamma = 43$ deg flap produces a maximum C_l of 1.9, very near that observed at higher Reynolds numbers. At $Re = 7.0 \times 10^4$ and 9.5×10^4, the maximum lift coefficients for the $\gamma = 43$ deg flap are 2.0 and 1.8. At $Re = 1.2 \times 10^5$, the maximum lift coefficient is 2.0 with the $\gamma = 75$ deg flap (not shown). Shallower flaps perform slightly less well here and, because clean wing performance is beginning to improve, these devices do not have a large beneficial effect.

The oil flow visualization in Fig. 6 shows that the leading-edge flaps and wires significantly delay separation. This suggests that under these conditions they can promote transition. However, unlike the surface-mounted trip, these leading-edge devices are ineffective at low angles of attack. This sudden change in flow behavior is likely a result of the device's position relative to the leading edge of the airfoil. The vortex shedding behind a leading-edge wire would pass under the airfoil at low angles of attack. At a certain angle of attack, however, the flow disturbances would begin to pass over the upper surface of the airfoil, altering the development of the boundary layer. This explains the increasing critical angles of attack observed as the flap deployment angle increases. The effect of the leading-edge flap is similar, with disturbances generated at the sharp leading edge.

Conclusions

Observations of birds in flight have led to the discovery of a flap of feathers which deploys at the leading edge of the wing. In the current work, a steady-flow case has been developed to compare the effects of an idealized leading-edge flap to those of surface-mounted transition trips at low Reynolds numbers. This series of experiments suggests that the leading-edge flap works as a transition trip, introducing disturbances into the flow which, at high angles of attack, propagate over the upper surface of the wing preventing the formation of a laminar separation bubble. Because of the geometry and placement of such a flap, it becomes effective only at high angles of attack, the same flight regime in which the avian flap has been observed. A study of flap design parameters has shown that shallower flap deployment angles become effective at lower angles of attack. Leading-edge flaps were found to be effective high-lift devices at Reynolds numbers as low as 4.0×10^4, giving higher maximum lift than achieved with a surface-mounted trip. These results suggest that a leading-edge flap can be used as a high-lift device for low Reynolds number flight vehicles.

Acknowledgments

The authors gratefully acknowledge the funding provided by the U.S. Air Force Research Laboratory, the National Science Foundation, and the Winston Churchill Foundation.

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