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Wind-Tunnel Tests of Flap Gap Seals on a Two-Dimensional Wing Model

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Nomenclature

$C_{L_{max}}$ = airplane or wing lift coefficient
$C_{l_{max}}$ = section lift coefficient
$C_{l_{max_f}}$ = section lift coefficient with flaps deflected
$C_{l_{max_0}}$ = section lift coefficient with zero flaps
Re = Reynolds number based on chord length
S = wing area
S_f = area of wing segment containing flaps
α = angle of attack
δf = flap deflection angle

Introduction

A COMMERCIALLY marketed drag reduction kit was installed and flight tested on a Piper Arrow II by the first author of this Note in 1989.[1] Predominant among the devices included were gap seals for both the wing flaps and ailerons, but several fairings for flap hinges, fuel-tank-attach screws, and exposed portions of retracted wheels were also included. The primary purpose of the tests was to evaluate the effectiveness of these devices in reducing drag. Since the effect of each device was too slight to be measured individually, the entire kit was installed and tested by measuring various performance parameters. The results showed a slight reduction in parasite drag coefficient of about 18 counts, or 7% below that of the unmodified aircraft.

An unexpected result of these tests was a slight reduction in maximum lift coefficient and corresponding increase in stall speed, with the modifications installed. The change was slight, but occurred in all cases tested. The increased stall speed was about 1 or 2 mph. A senior thesis project[2] verified these results in a wind tunnel, although at very small Reynolds numbers ($Re = 1.43 \times 10^5$–1.87×10^5). This model was also three dimensional.

Flap gap seals were also investigated as part of the Advanced Technology Light Twin-Engine airplane program.[3] Although wind-tunnel tests indicated greater maximum lift with the seals in place, flight tests of the full-scale aircraft revealed the opposite. The flight tests were only performed with flaps retracted; however, the sealed flaps reduced the maximum lift coefficient by 0.19, or 5 mph higher stall speed, compared to the unsealed condition.

Although no data have been published, Mooney Aircraft Corporation tested gap seals on the Mooney TLS. Conversations with Mooney engineers indicated that a slight drag reduction was achieved, which accounted for about a 2-kn increase in cruise speed. Careful adjustment and testing was required to achieve this result, however, without altering the stall speed.

Since very little information could be found on the effects of gap seals, especially those on stall speed, it was decided to pursue further investigation. A thorough aerodynamic study of the effects of flap gap seals in a controlled environment of a wind tunnel was deemed necessary. Also, since the few previous tests that were done were primarily on three-dimensional wings, it was decided to approach this study from a two-dimensional aspect.

To compare the results with previous flight tests, the airfoil of the Piper Arrow II was used, namely a NACA 65_2-415. This airfoil was also utilized in the study of Ref. 2.

Procedure

A model was constructed for testing in the Pennsylvania State University low-speed wind tunnel, which has a test section of approximately 3.5 × 5 ft. The chord was 11.813 in., which represents a 3/16 scale of the full-size Piper Arrow. A 16-in. span was chosen, with large endplates to simulate a two-dimensional wing, which fitted into walls inserted within the tunnel.

Lift and drag forces were measured by use of an Aerolab six-component, pyramidal, strain gauge balance. Airspeed was determined by a ceiling-mounted pitot–static tube in the forward portion of the test section, which fed into a pressure transducer, and the resulting pressure differential displayed as voltage on a voltmeter. Both the balance and the pitot–static system were calibrated prior to actual testing. Tare runs were also made to determine the drag of the endplates and balance struts.

Tests were run at a speed near the highest sustainable speed of the tunnel (168 ft/s), which yielded a Re of 9×10^5. To gain some insight into Reynolds number effects, runs were also made at $Re = 6 \times 10^5$, or a speed of 112 ft/s. Since these Reynolds numbers were well below those of the full-scale airplane, a trip-strip was installed at the 30% chord position to fix the transition point. This location was chosen as a result of information in Ref. 4.

Runs were made at each of the four flap settings of the full-scale airplane: 0, 10, 25, and 40 deg. Data were taken at 14 points from −4 to +16 deg angle of attack, in 2-deg increments from −4 to +10, and 1-deg increments from 10 to 16 deg (the stall region). All tests were run with and without gap seals installed, and at both $Re = 6 \times 10^5$ and 9×10^5.

Flow visualization was performed by use of heavyweight cotton thread tufts taped to the wing. Twelve spanwise rows with seven tufts chordwise in each row were utilized, all equally spaced. Photos were made of the tuft patterns at angles of attack of 4 deg to full stall in 2-deg increments, and also 1 deg before stall. Oil flow studies were also conducted with a brightly fluorescing motor oil thinned with kerosene, and illuminated with uv lights.

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Results

Lift and drag coefficients were calculated from the measured forces by conventional nondimensionalizing methods. The coefficients were then corrected for wind-tunnel boundary effects, including horizontal buoyancy, solid blockage, wake blockage, and streamline curvature, as suggested by Rae and Pope.[5]

As anticipated, the most apparent difference between seal-on and seal-off conditions was the reduction in the maximum lift coefficient with the seal on. This situation occurred with practically every condition tested. The only exception was the 0-deg flap case at $Re = 6 \times 10^6$; the scatter in data here, however, leaves serious doubt as to the validity of this result. In all other cases, the $C_{l_{max}}$ was reduced when seals were installed. The change ranged from a minimum of 3% at $\delta f = 10$ deg to a maximum of 22% at $\delta f = 40$ deg, both at $Re = 9 \times 10^5$. Figure 1 shows this maximum condition, in both seal-on and seal-off conditions.

The advantage of the slotted flap is its ability to energize the boundary layer on the upper surface, and, hence, delay separation. It is this delayed separation that achieves greater $C_{l_{max}}$ than with simpler flap configurations. A reduction in $C_{l_{max}}$ would suggest a change in the separation pattern. This result was indeed apparent in the flow visualization studies.

Figure 2a shows the tuft pattern for $\delta f = 40$ deg and $\alpha = 8$ deg at $Re = 9 \times 10^5$ in the normal seal-off condition. The flow appears to be well attached near the trailing edge of the flap. With the seal on, however, as shown in Fig. 2b, separation occurred well ahead of the flap. This change in separation location was also verified in the oil flow studies. It would appear that the seal interferes with the flow through the gap, and, in so doing, reduces the effectiveness of the energizing of the upper surface boundary layer.

The effect of the gap seal on drag coefficients was much less apparent. The results were mixed, and in many cases,

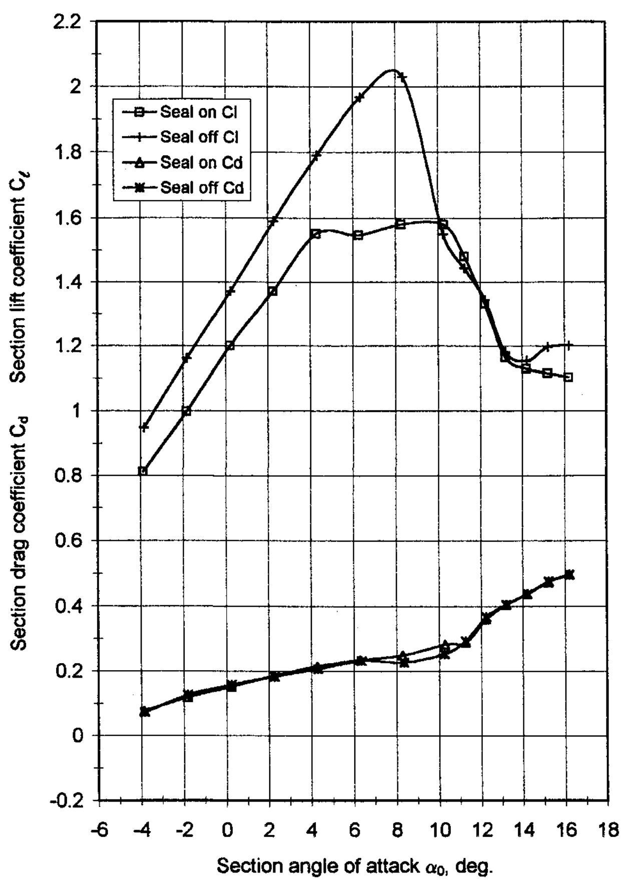

Fig. 1 Section characteristics for $Re = 9 \times 10^5$ and $\delta f = 40$ deg.

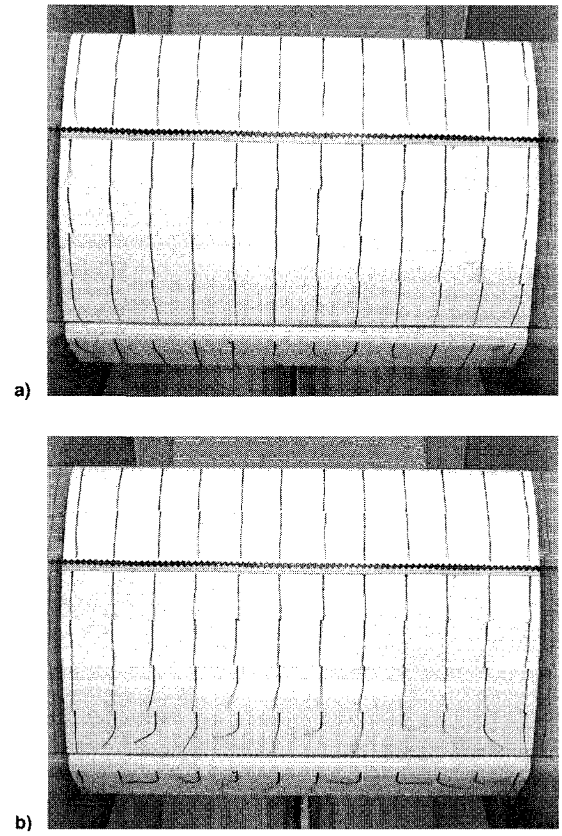

Fig. 2 Tuft flow visualization for $Re = 9 \times 10^5$, $\delta f = 40$ deg, and $\alpha = 6$ deg: a) without seal and b) with the seal on.

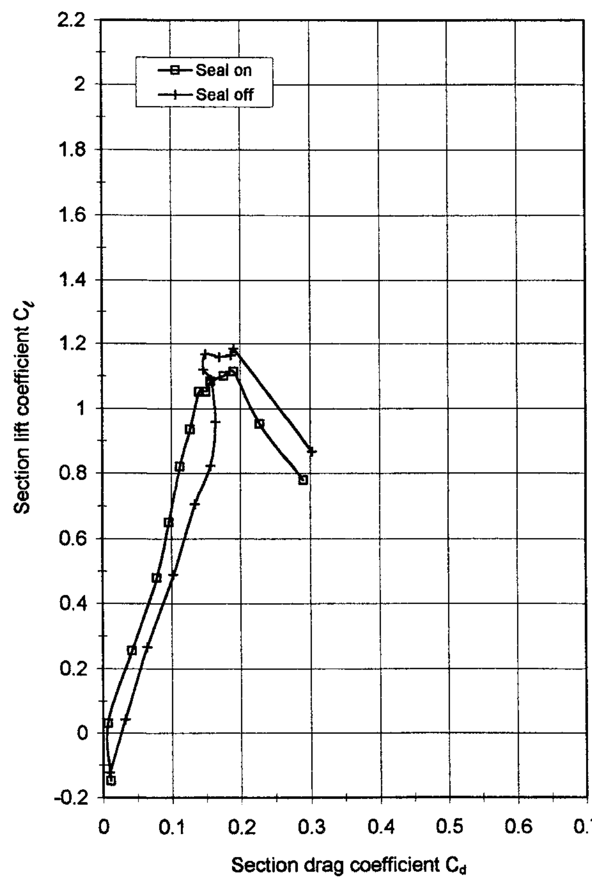

Fig. 3 Section lift coefficient vs drag coefficient for $Re = 9 \times 10^5$, $\delta f = 0$ deg.

showed very little, or no, difference between the two conditions. Since the primary purpose of the seal is to reduce drag in the cruise and climb conditions, the 0-deg flap case would seem most significant. Figure 3 shows the drag to be somewhat reduced over a fairly wide range of C_l for the $Re = 9 \times 10^5$ case. However, at $Re = 6 \times 10^5$, the results were just the opposite. At higher flap deflections, similar plots revealed no clear trend, with the two curves being nearly identical, or slightly crossing each other at various C_l values.

It should be noted that the drag coefficients determined seem rather high for these Reynolds numbers. This result could be attributed to several factors. First, the oil flow studies revealed a leading-edge separation bubble with turbulent reattachment for angles of attack above 6 deg. Secondly, the balance used has a history of some error in the absolute values of drag indicated. However, the relative values of drag for the seal-on case compared to the seal-off case should be valid.

The angle-of-zero lift as determined by these tests showed very good agreement with NACA results at higher Reynolds numbers as presented in Ref. 6. The lift–curve slope also seemed to be comparable to previous data. Seal condition seemed to have little effect on this parameter.

Conclusions

Wind-tunnel tests of a 3/16 scale, two-dimensional wing utilizing a 65_2-415 airfoil at $Re = 6 \times 10^5$ and 9×10^5, with and without flap gap seals revealed the following conclusions.

1) Installation of the flap gap seals reduced the maximum lift coefficient at all flap settings tested. The maximum reduction was 22% for the maximum flap deflection angle of 40 deg.

2) Flow visualization revealed that the gap seal significantly altered the flow pattern over much of the wing, even well forward of the flap. The normal wing with no seal had a greater extent of attached flow than the wing with gap seal in place, for all cases tested.

3) No clear trend was revealed in the difference in drag between the seal-on and seal-off conditions. Some indication of drag reduction with the seal in place was noted for midrange angles of attack in the 0-deg flap case at the higher Reynolds number. This trend reversed, however, at the lower Reynolds number.

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