A New and Less Complex Alternative to the Handley Page Slat

Arthur L. Williams*
Northrop Corporation, Hawthorne, California

This paper investigates various devices designed to delay leading-edge stall and illustrates the superiority of the rotating leading-edge flap. The popular Handley Page slat allows the accelerated air coming from below to be ejected at the abrupt change in chord line. This delays the stall separation and improves the $C_{L\max}$, thus permitting a higher angle of attack. The Kruger flap hangs down to split the air selectively; however, the abrupt change in airflow at the knee prevents the device from achieving as high a stall angle and $C_{L\max}$ as desired. A flexible fiberglass Kruger flap incorporates the geometry of an "ever-opening spiral." This flap allows a high lift coefficient at high inflow angles, but it is a complicated device. The "ever-opening spiral" concept has been employed in the design of a four-bar linkage device that meets the desired requirements of compact storage. Its simplicity has led to time and cost reductions in design, fabrication, and maintenance. In its simplest form, it uses no cove slots or high-pressure air for boundary-layer control; yet these options can be incorporated for STOL applications where a $C_{L\max}$ near 6 is desired. The device may be retrofitted to update existing aircraft or even be "jury-rigged" in a temporary way to permit quick evaluations of potential performance and handling qualities.

Requirements for a Superior Device to Delay Leading-Edge Stall

ANY device designed to delay leading-edge stall must meet the following criteria:

1) Be capable of delaying flow separations to large angles of attack (or large inflow angle).

2) Be stowable in the most forward portion of the wing section (10% chord or less) without the mechanism penetrating the fuel tanks behind the front spar.

3) Have an extremely simple drive mechanism and supports. Supports and torque drive hinges should be spaced close enough to prevent deflection or torsion windup in the leading-edge device.

4) Should not deflect under the air load and cause gaps or air leaks in the stowed position.

Existing Methods for Delaying Separation with Increasing Angle of Attack

To alter the wing section geometry in order to delay airflow separation, the obvious starting point is to increase the leading-edge radius (compare Figs. 1 and 2). This radius increase can be achieved by changing the family of airfoils from a laminar flow section with a small nose radius (Fig. 1) to a supercritical airfoil with a larger nose radius (Fig. 2). Of course, increasing the thickness-to-chord ratio (t/c) will usu ally give a substantial increase in the leading-edge radius. Airfoils in the same family usually have leading-edge radii increased proportionally to $(t/c)^2$.

The next most obvious approach is to droop the leading-edge camber line forward of the 15% chord. This is also powerful in delaying separation, even with the thinner airfoils (i.e., $t/c = 9\%$ or even as low as 4%) used on fast military aircraft. For example, Raisbeck[1] reworked the leading edge of a Learjet business aircraft, the geometry of which was similar to that shown for the tip section in Fig. 3 ($t/c = 9\%$). This leading edge was retrofitted on existing Learjets. The overall reduction in the takeoff and approach speeds varies from 16 to 23 knots, depending on the airplane and configuration.

The air minimum control speed was reduced to values below the stall speed for model 25 and reduced 28 knots for model 24.

With this leading edge, a significant reduction occurred in cruise drag, notably under long-range cruise conditions. The drag reduction level has been substantiated by back-to-back flight tests with a fully instrumented and calibrated Learjet. Typically, 10-15% reductions in overall fuel consumption have been reported by owners.

In order to take advantage of the ability to droop the forward chord line at low speed and raise it at high speeds, the leading-edge flap was conceived. (Fig. 4 shows a thickness-to-chord ratio of approximately 10%.) The leading-edge flap has become very popular with supersonic aircraft with a sharp or relatively sharp leading edge on thin wings (around $t/c = 5\%$, see Fig. 5). In addition to using it for landing and takeoff, it is sometimes used to protect the leading edge from early separation when the wing is pulling high load factors at combat maneuvering speeds.

Since this leading-edge flap has an abrupt change in chord line or camber line, the airflow has difficulty turning the corner without separating. The natural step is to leave a slot behind the flap to allow the accelerated air from below to be ejected at the aft end of the slot. This is a natural (unpowered) type of boundary-layer control (BLC). See Fig. 6. Called a Handley Page slat, this type of leading edge device has been widely used for several decades, i.e., many high-subsonic jet airliners are equipped with a Handley Page slat.

Another less complex leading-edge device that helps delay separation at the leading edge is the Kruger flap (Fig. 7). The lower surface swings out of the bottom of the wing and has a small bulb nose. Since the stagnation point is low at high lift coefficients, the Kruger flap hangs quite low to split this air selectively. The abrupt angle change in the airflow occurs at the knee similar to the leading-edge flap, which prevents this device from achieving as high a stall angle and $C_{L\max}$ as the

Presented as Paper 85-0352 at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, Jan. 14-17, 1985; received Feb. 2, 1985; revision received Oct. 21, 1985.

*Senior Technical Specialist, Aircraft Division. Associate Fellow AIAA.

Handley Page slat. Boeing uses the Kruger flap on the inboard one-third of the wing span of the 727 airliner and a Handley Page slat on the outboard two-thirds. This allows the tip to achieve higher angles than the root before stalling and thus helps prevent a tip stall pitch-up.

In Fig. 8 is shown some section data (infinite aspect ratio) of the lift coefficient vs angle of attack for an airfoil with a slat. These data came from a NACA Technical Note.[2] The NACA 64A010 symmetrical airfoil was tested with no flap, with a split flap, and with a double-slotted flap. Note that when no slat was used the maximum lift occurred at a 10 deg angle of attack with no aft flap; with a split flap, this maximum lift drops to 6 deg; and with a double-slotted flap, it drops to 0 deg.

When a 17% chord slat is added, the plain airfoil has twice the maximum lift and stalls at 22 deg angle of attack. When this slat is added to the airfoil with a split flap, the stall occurs earlier at 17 deg. This stall occurs at 9 deg when the slat is installed in combination with a 25% chord double-slotted aft flap.

The significant conclusion drawn from Fig. 8 is that the angle of attack at stall decreases as the maximum lift coefficient increases. This gives a locus of stall points that moves up and to the left on the plot. This phenomenon does not occur with the new leading-edge device reviewed later in this paper.

Boeing increased the performance of the Kruger flap by flexing the flap skin to approach an "ever-opening spiral" (Fig. 9). The device is used on the Boeing 747, with only a cove slot to allow natural unpowered BLC. This same device is used on the Boeing YC-14 where its effectiveness is enhanced by power blowing air at the cove slot to augment the air from below. Of course, this is a very complex leading-edge device, but it will protect the leading edge from early separation and help to achieve very high lift coefficients and high inflow angles. Most applications do not warrant this complexity and the resulting high cost of design, manufacture, and maintenance.

This flexible fiberglass leading-edge flap does illustrate the need for a device having a spiral geometry with a reduction

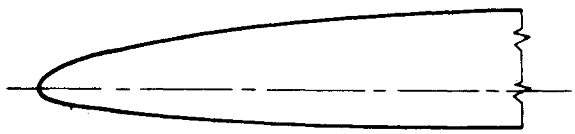


Fig. 1 Laminar flow airfoil with small nose radius.

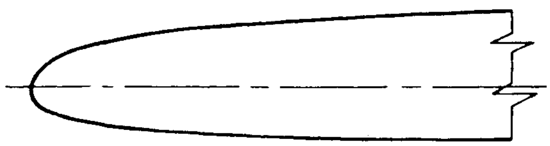


Fig. 2 Supercritical airfoil with larger nose radius.

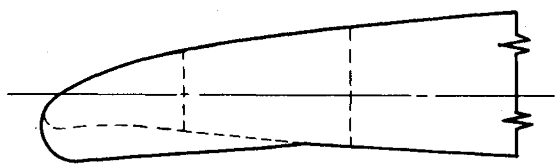


Fig. 3 Camber line dropped forward of 15% chord.

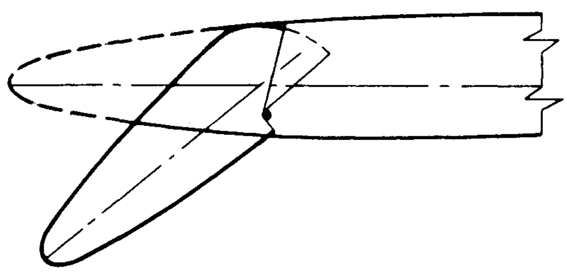


Fig. 4 Leading-edge flap, wing section ($t/c = 10\%$).

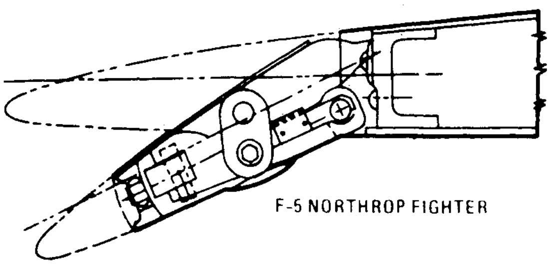
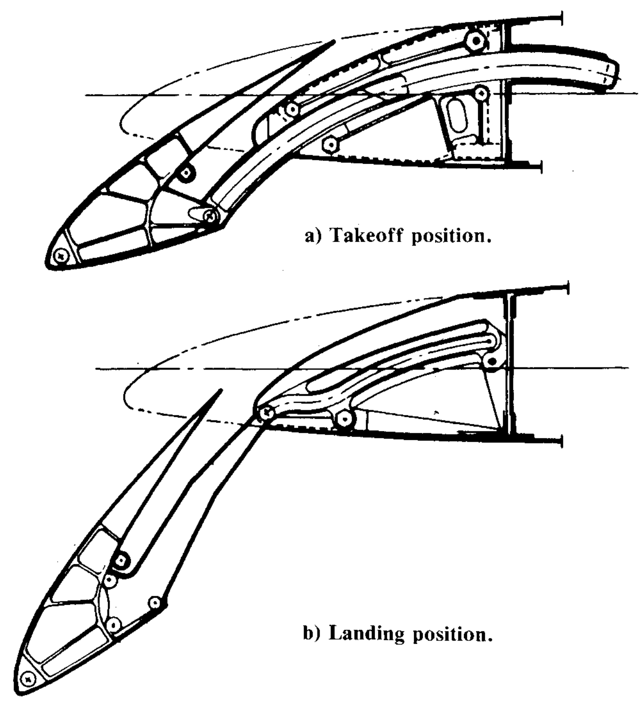


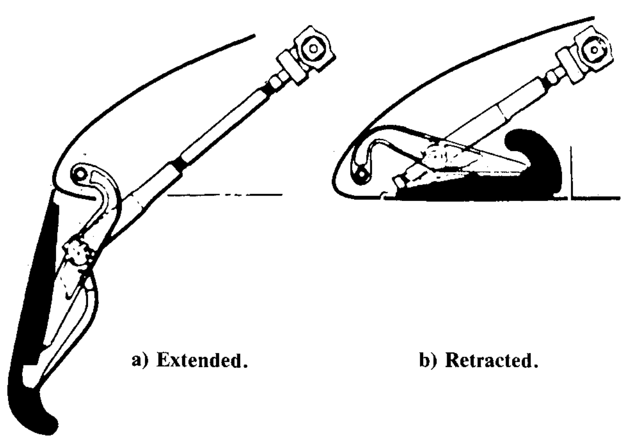
Fig. 5 Leading-edge flap, wing section ($t/c = 4\%$).



a) Takeoff position.

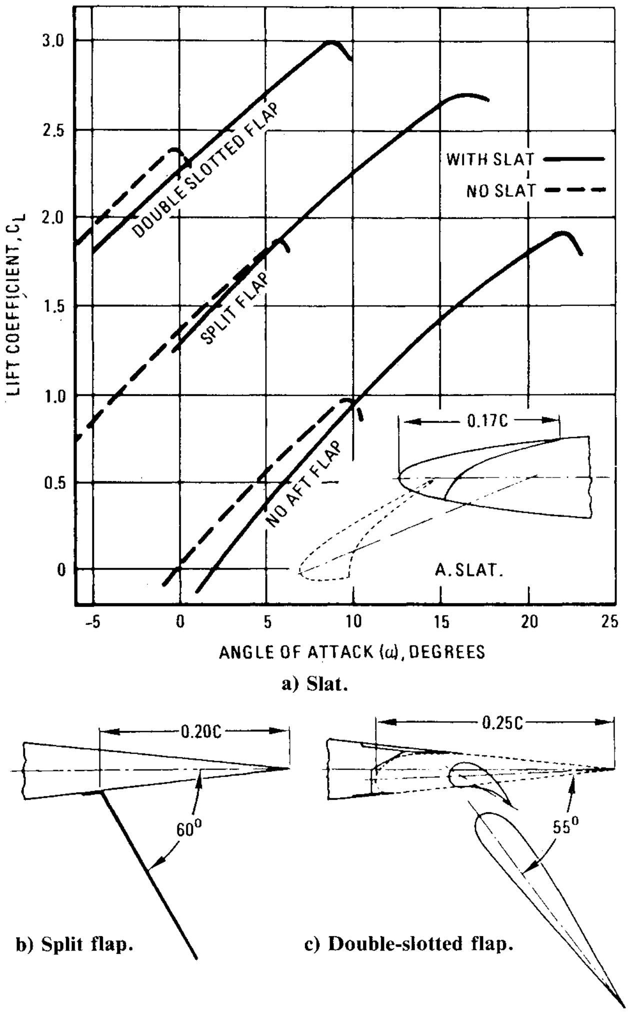
b) Landing position.

Fig. 6 Handley Page leading-edge slat installed on Boeing 767.



a) Extended. **b) Retracted.**

Fig. 7 Kruger leading-edge flap.



a) Slat.

b) Split flap.

c) Double-slotted flap.

Fig. 8 Effect of leading-edge slat on NACA 64A010 airfoil with and without flaps.

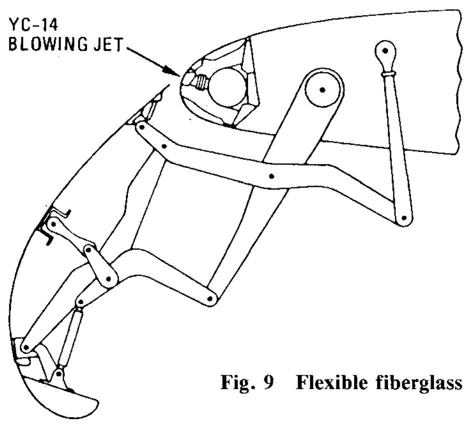


Fig. 9 Flexible fiberglass leading-edge flap.

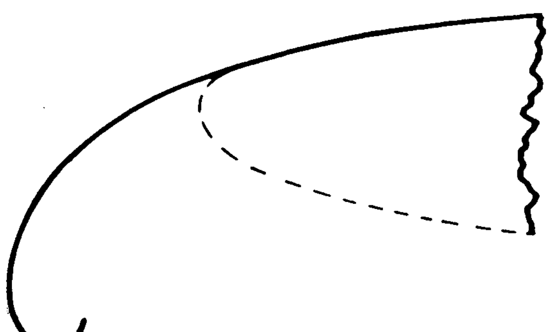


Fig. 10 Ever-opening spiral.

in the slope of curvature as the air moves back along the surface (Fig. 10). The air stagnates at the tight part of the curvature where the pressure is highest. As the airspeed increases, the pressure is reduced according to Bernoulli's principle. The lower the pressure, the more easily the air can separate as it moves around the leading edge. Therefore, it is desirable for the curvature to be less and less abrupt as the air accelerates. The closer this geometry can approximate an "ever-opening spiral," the less need there is for a cove slot or BLC to reattach the flow at a sharp corner or knee.

New Concept for Delaying Separation

A leading-edge device developed by the author is shown in Figs. 11 and 12.[3] This patent disclosure is the chief contribution made by this paper. Its geometry is a simple four-bar linkage that achieves this "ever-opening spiral" effect, yet is much less complex than the Boeing flexible leading-edge Kruger flap (Fig. 9). The device fulfills the requirement of being stowable in a small portion of the leading edge. A cove slot can also be added if performance requirements demand it. It can also carry high-pressure air down the leading-edge tube and eject it in the cove for BLC similar to the method used in the Boeing YC-14 aircraft (Fig. 9).

In addition, this tube can be used to carry hot air along the leading edge to anti-ice it. This tube rotates 126.8 deg, but it does not translate forward and down as does a tube in the leading edge of a Handley Page slat. This complication quite often causes a Handley Page slat to be anti-iced electrically, which generally is less efficient and more expensive.

This leading-edge geometry has been tested in Lockheed's low-speed wind tunnel.[4,5] The model geometry is shown in Fig. 13. The model wing section had a chord of 18 in. and an aspect ratio of 6 (no sweep). A NACA 0012 airfoil was used. The Reynold's number tested was as high as 1.2×10^6.

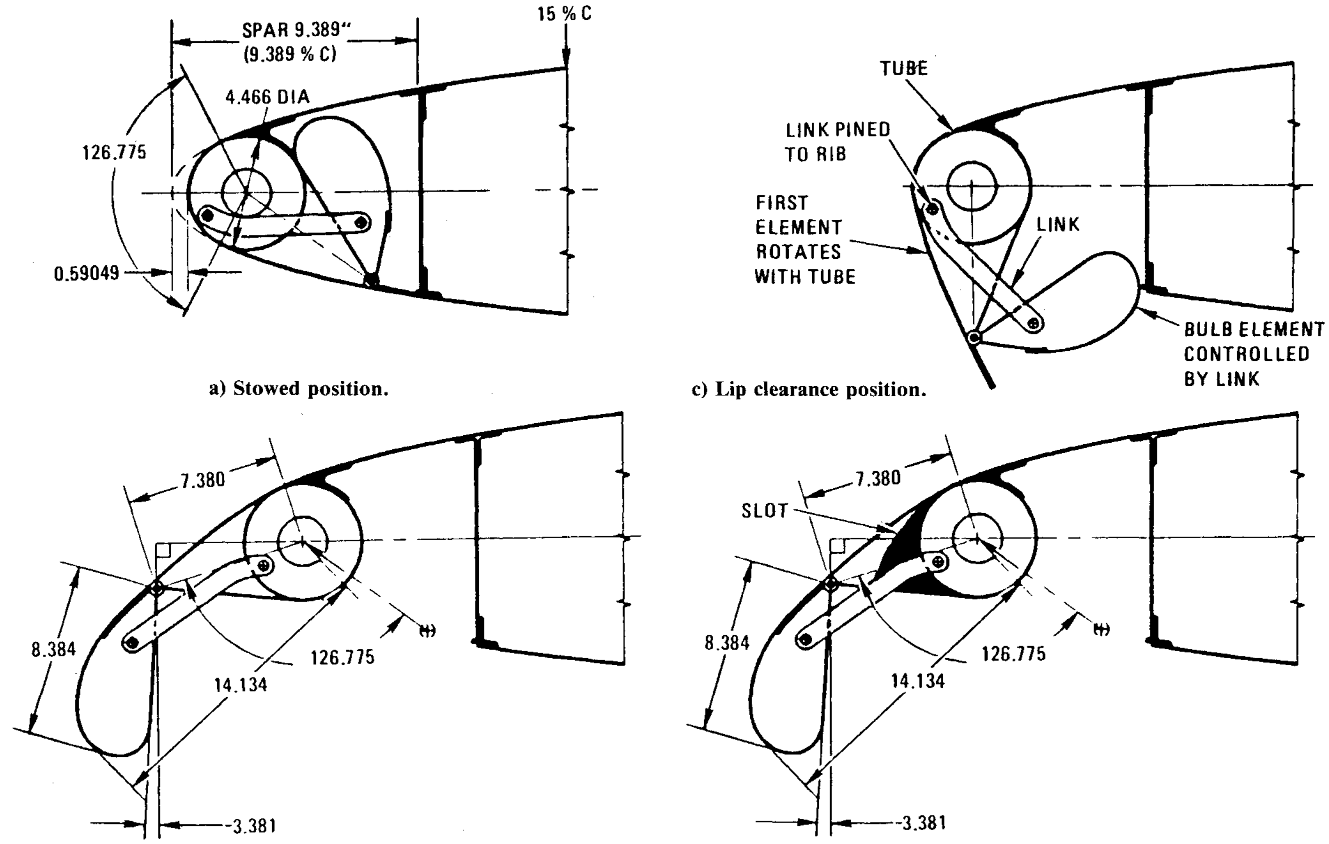
This concept was tested with and without a cove slot. Figure 14 compares a cove slot (Fig. 13a) with a device with no cove slot (Fig. 13b). Run 18 had a split aft flap and a cove slot at the leading edge. An increase in lift coefficient of 0.76 was obtained. Nevertheless, run 43, which had no cove slot, obtained the same maximum lift coefficient. The main difference is the more abrupt stall that occurred when there was no slot. Both have an angle of attack that is, for most applications, above the desired range for an aspect ratio 6 wing.

Both configurations were tested with and without blowing high-pressure air down the leading edge tube and out over the leading edge. Although $C_\mu = 0.155$ (blowing coefficient) was the highest attained on the first set of tests, this paper reviews only $C_\mu = 0.077$ and 0.039 data in Fig. 15 because an angle of attack of over 28 deg was achieved, which is higher than the usable range. Note that the stalls shown in Fig. 15 do not slant up and to the left as they did with the Handley Page slat in Fig. 8.

Even when the aft split flap is omitted, the leading-edge slot contributes mainly to the gentleness of the stall. Run 82 had the slot; runs 9 and 11 had no leading-edge device.

One may ask how the rotating leading-edge flap compares with the Handley Page slat. A comparison was made between the NACA 23012 (Fig. 16) airfoil[6] and the results of Lockheed wind tunnel tests, as shown in Fig. 16. Note that with no aft flap there is only a slight advantage to the Handley Page slat. Much more time was spent to tune the slot gap and to position the slat than with the rotating leading-edge flap. The most noticeable difference is apparent with a 60 deg split flap. When the rotating leading-edge flap achieved a $C_{L\max} = 2.57$ between $\alpha = 21$ and 22 deg, the Handley Page slat showed a $C_{L\max} = 2.16$ at $\alpha = 21.5$ deg.

The Handley Page slat operated up to very large angles without abruptly stalling, as evidenced by the relatively constant lift coefficient in this region. Whether this additional angle of attack is desirable depends on the requirements of the configuration.



a) Stowed position.

c) Lip clearance position.

b) Extended position.

d) Extended position with slot.

Fig. 11 Williams simplified Handley Page slat.

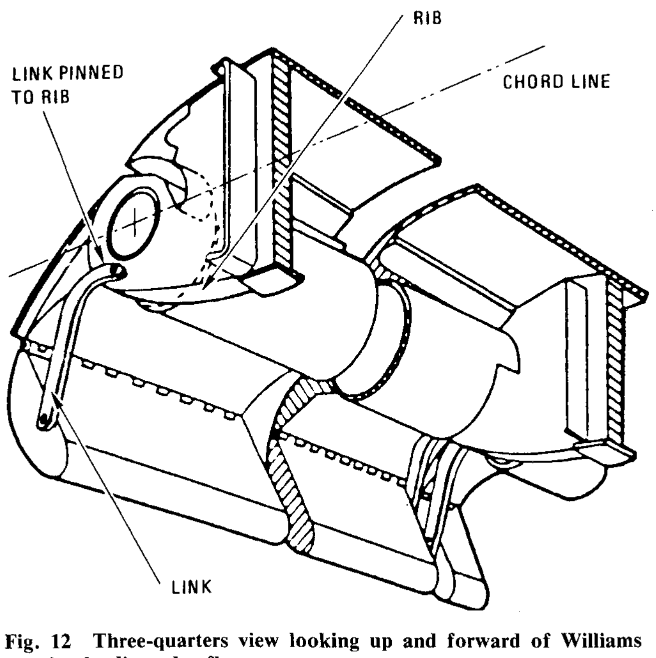


Fig. 12 Three-quarters view looking up and forward of Williams rotating leading-edge flap.

With a simple aft flap, using no blowing for boundary-layer control, the flap could stall at less than 10 deg angle of incidence when no leading-edge device was used. This is illustrated in Fig. 17 (a photo taken in the late 1950s in the Fairchild Aircraft smoke tunnel).

Figure 18 shows that, when considerable blowing is applied at the leading edge of the aft flap, the inflow and outflow angles are extremely high. Note also that the angle of incidence to the wind tunnel is near zero. This wing section could use a good leading-edge device. This would allow the air to remain attached as it rounds the leading edge, which should allow a considerably greater angle of attack.

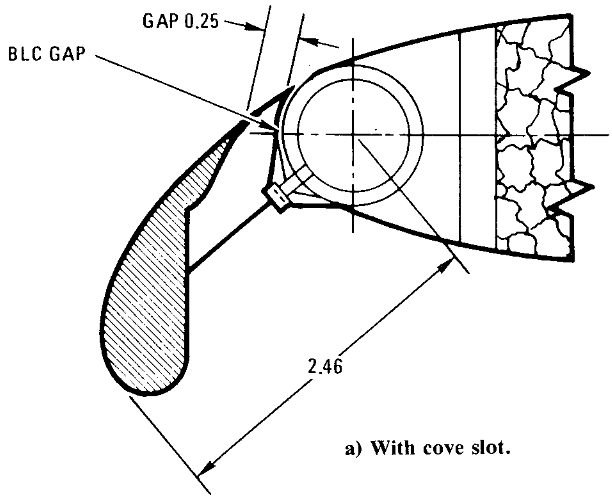
Lockheed has tested a circulation control wing (CCW) with considerable blowing (up to $C_\mu = 0.46$) at both the leading and trailing edges.[7,8] These tests demonstrated the increase in angle of attack that can be obtained by an effective leading-edge device.

The circulation control wing (Fig. 19) model was always tested with blowing at the trailing edge. When the rotating leading-edge flap was installed, it too was blown. One-third of the air went to the leading edge. When the leading edge was not blown, the nose of the plain NACA 0012 airfoil was used. Some of the results of these tests are shown in Fig. 20. This model was a derivative of the 18 in. chord aspect ratio 6 model shown in Fig. 13. Note that with no leading-edge device and with each increase in the blowing coefficient C_μ the model stalled at a lower angle. Run 135 at $C_\mu = 0.46$ stalled at -1 deg. This is similar to the wing in Fig. 18.

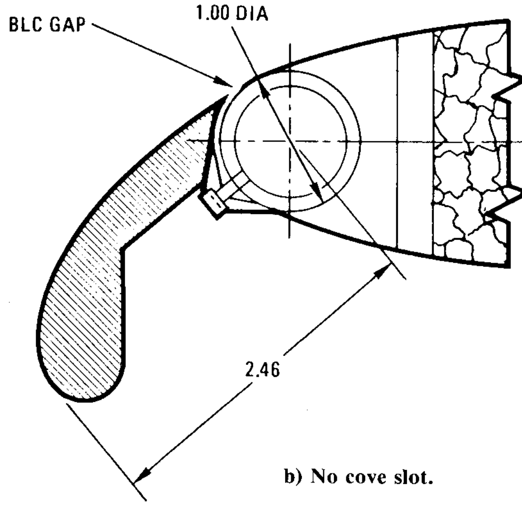
With a little blowing ($C_\mu = 0.06$) as in run 136 of Fig. 20, the CCW wing works much the same as the flapped wing in Fig. 17. This wing at 10 deg incidence is fully stalled. Run 136 in Fig. 20 would indicate that at 6 deg the flapped wing of Fig. 17 might reach a $C_{L\max} = 2.4$. Therefore, some degree of correlation exists.

The C_L vs α curve of Fig. 20 shows that when the rotating leading-edge flap was installed, there was an outstanding increase in both the angle of attack α and $C_{L\max}$, the latter almost reaching 6.0. This is exceptionally good for a wing with an aspect ratio of 6.

A trend can be noted in Fig. 20. There is a slight increase in the angle of stall as the blowing coefficient of the leading edge increases. Note that the locus of the stall points slants up and to the right for the higher C_μ values.



a) With cove slot.



b) No cove slot.

Fig. 13 Model leading-edge configurations on an 18 in. chord wing (as tested in Lockheed low-speed wind tunnel).

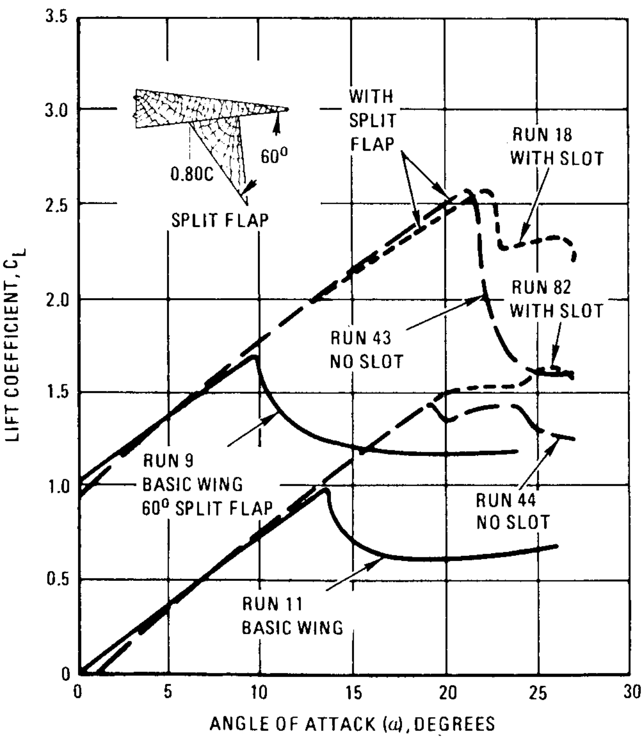


Fig. 14 Comparison of leading-edge flap with and without cove slot.

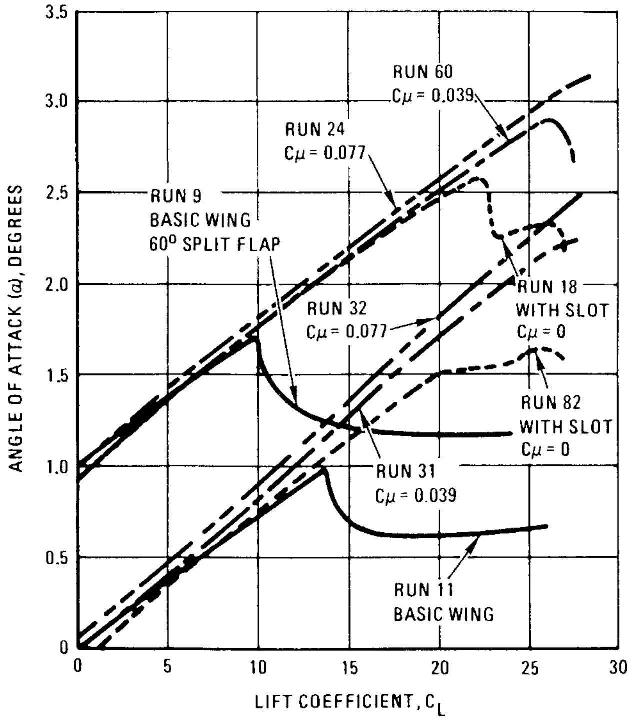


Fig. 15 Boundary-layer control added to rotating leading-edge flap.

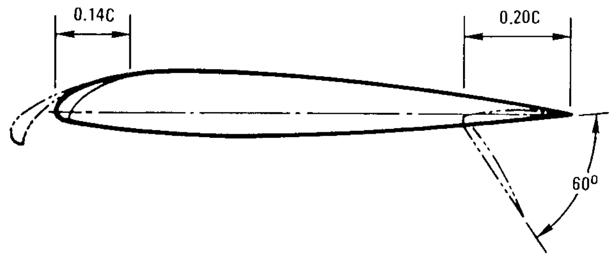


Fig. 16a NACA 23012 airfoil with a Handley Page slat and split flap.

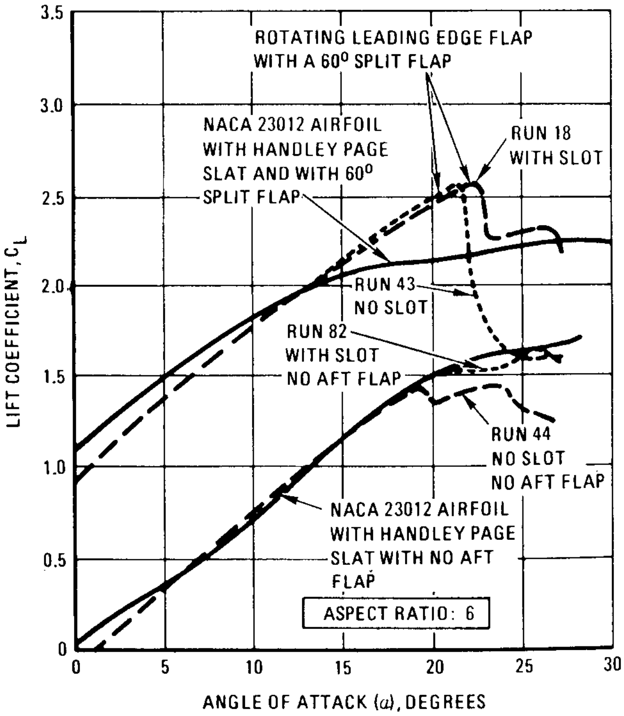


Fig. 16b Comparison of a NACA 23012 airfoil with a Handley Page flap and a rotating leading-edge flap with and without a slot.

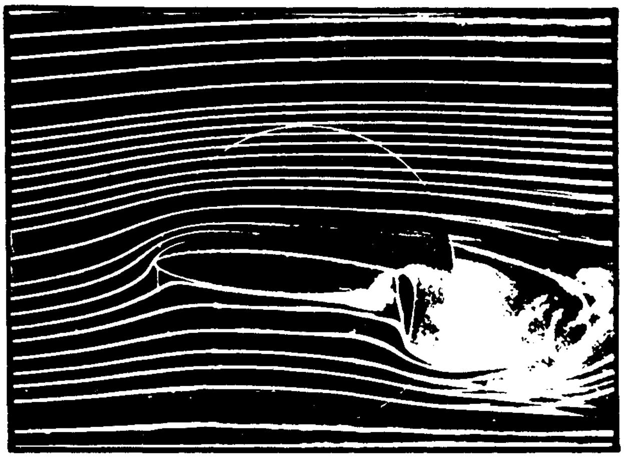


Fig. 17 Unblown simple aft flap.

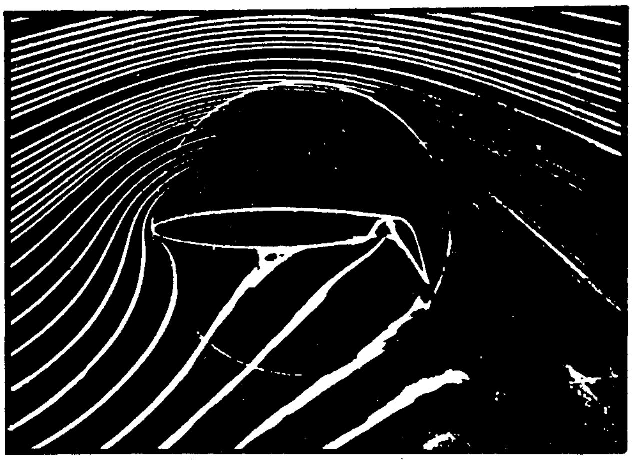


Fig. 18 Wing blown at leading edge of aft flap.

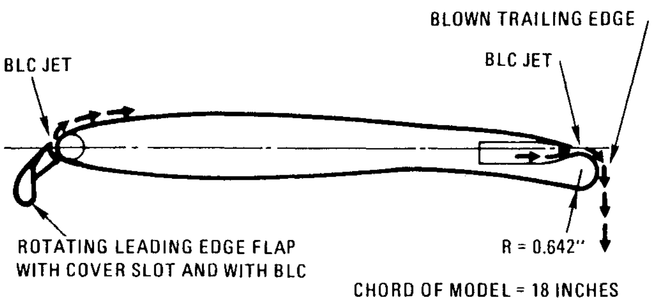


Fig. 19 Circulation control wing.

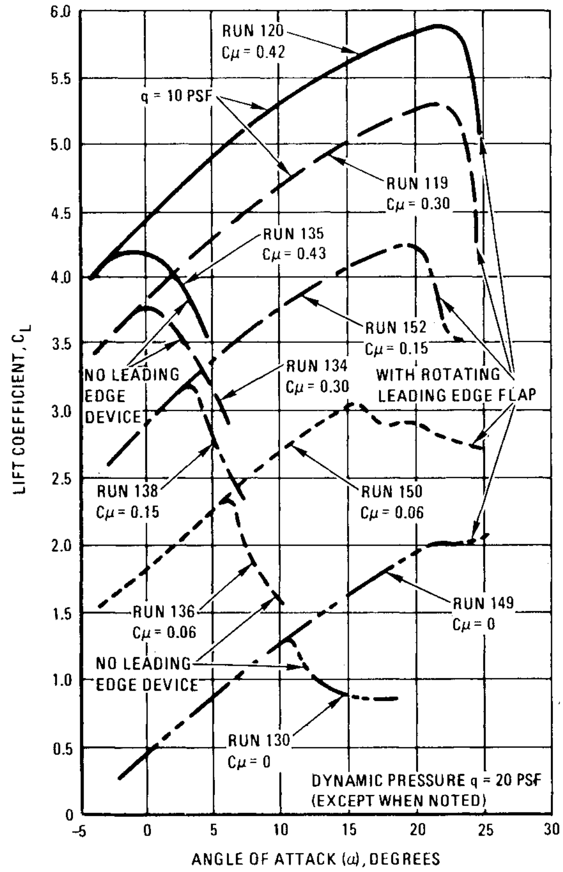


Fig. 20 Performance of circulation control wing.

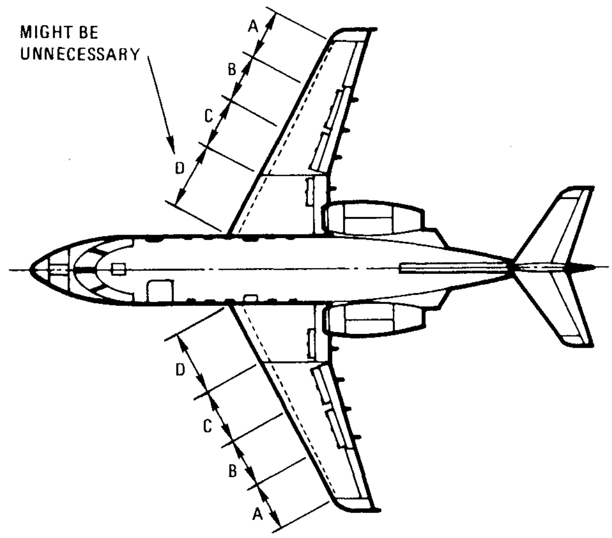


Fig. 21 Portions of wing to be "jury-rigged" with high-lift devices.

Probably the more appropriate use of this new device is not in the more elaborate STOL applications such as the CCW wing, but rather in its simplest form with no cove slot, no blowing, etc. The gain in performance vs the cost to install is best demonstrated in such applications, because its outstanding superiority is in the physical characteristics listed earlier. These advantages, along with the good aerodynamic performance qualities, make this device a very competitive candidate for most new aircraft that need a wing leading-edge device and have an airfoil with a substantial leading-edge radius.

This device should be considered not only for new applications, but also for retrofitting on existing aircraft not having such equipment that could achieve better low-speed flight characteristics and performance by using it. Before a company invests too much of its resources in designing and retrofitting this device, it could (for flight test purposes) "jury-rig" a strapped-on leading edge that will have the same contour as the rotating leading-edge flap in the extended position. This can be done for experimental flight test only and with only one pair of parts or sections at a time (see Fig. 21), starting with the outboard portions. The extension can be fastened externally over the outside of the existing leading edge and pick up existing rivets in the nose ribs. One possible solution is shown in Fig. 22.

The increase in drag from leaving the leading-edge flaps extended for the whole test flight will require only a small increased in power. When the flight test is completed, the increased improvement in low-speed aerodynamic performance

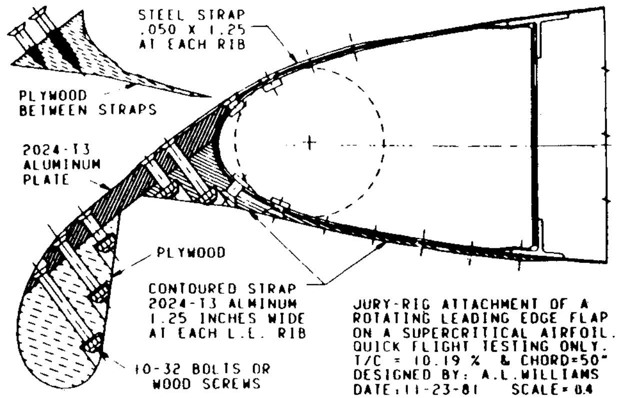


Fig. 22 Jury-rig attachment of a rotating leading-edge flap on a supercritical airfoil (quick flight testing only).

and handling characteristics can be evaluated against the cost of installation and certification.

This will require a preliminary design to evaluate and determine the cost of the installation. The design should consist of determining the number of supports, the number of torque hinges and the method of driving them, the amount of bending deflection and torsional windup, and the prediction of the deflection under load that might create air gaps. It is the author's belief that, although this appears to be a great deal of work, it will be considerably easier and less expensive than installing any of the other leading-edge devices of comparable performance.

Conclusion

For the past four or five decades, extensive time and ingenuity have been focused on developing a leading-edge device that delays flow separation or reattaches the flow at a high lift coefficient. The devices that perform best are also the most complex and expensive. Some deflect under load and allow large air gaps or cause additional complications in order to prevent cruise performance loss. Although the Handley Page slat has remained popular for decades it now has a rival. This new leading-edge device not only delays the stall to a large lift coefficient, but also the stall can be delayed to a higher angle of attack than with the Handley Page slat.

The rotating leading-edge flap also rivals the flexible fiberglass Kruger flap used on the Boeing 747, because both form an "ever-opening spiral" that gives a locus of stall points on the C_L vs α curve that moves up and to the right with increasing angle of attack and lift coefficient.

The most important advantage of the rotating flap is that its remarkable performance is combined with reduced cost and complexity, as well as other advantages listed as requirements for a superior leading-edge device in the introduction.

Acknowledgment

The wind tunnel testing reported in this paper was performed at Lockheed California Company.

References

[1]Raisbeck, J.D., "The Mark II Learjet, From Concept to Certification," SAE Paper 760471, 1976.

[2]Kelly, J.A. and Hayter, N.-L. F., "Lift and Pitching Moment at Low Speeds of the NACA 64A010 Airfoil Section Equipped with Various Combinations of a Leading-Edge Slat, Leading-Edge Flap, Split Flap, and Double-Slotted Flap," NACA TN 3007, Sept. 1953.

[3]Williams, A.L., "Leading Edge Flap for an Airfoil," U.S. Patent 4,398,688, Aug. 16, 1983.

[4]Shibata, H.H., "Low Speed Wind Tunnel Test of a Rotating Leading Edge Flap With and Without BLC and of Trailing Edge Devices all Mounted on a Wing of Aspect Ratio Six," Lockheed Rept. LR 29610 (L-466), Oct. 23, 1980.

[5]Williams, A.L., "Summary Report of Low Speed Wind Tunnel Test of a Rotating Leading Edge Flap With and Without BLC on a Wing of Aspect Ratio Six," Lockheed Rept. LR 29696, Feb. 4, 1981.

[6]Schuldenfrei, M.J., "Wind-Tunnel Investigation of an NACA 23012 Airfoil with a Handley Page Slat and Two Flap Arrangements," NACA War Time Rept. L-261, Feb. 1942.

[7]Martin, R., "Low Speed Wind Tunnel Test of a Circulation Control Wing (CCW) Concept," Lockheed Rept. LR 29791, June 5, 1981.

[8]Williams, A.L., "Summary Report of Low Speed Wind Tunnel Test of a Rotating Leading Edge Flap on a Circulation Control Wing of Aspect Ratio Six," Lockheed Rept. LR 29821, April 20, 1981.