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Some Aerodynamic and Operational Problems of STOL Aircraft with Boundary-Layer Control

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A summary is presented of problems encountered during flight tests of STOL aircraft using boundary-layer control for high lift. A number of vehicles using boundary-layer control by suction through distributed perforations have been flight tested in this country and abroad during the past ten years. Several aerodynamic characteristics peculiar to this method of increasing lift have become apparent. Specifically, the theoretical methods used for the determination of the distribution of the required perforations are described and the agreement between these theories and experimental measurements is discussed. The requirement for more fundamental information concerning the effects of suction on the characteristics of the turbulent boundary layer, such as surface shearing stress, is emphasized. The effects of weather and aging on the perforations is mentioned in this regard. Separation of the flow at the wing leading edge resulting from locally high adverse pressure gradients is discussed and several methods for delaying or preventing this separation are suggested. The effects of various intersections, protuberances, and propeller slipstream effects are analyzed. Various flap configurations are examined and their effects upon the flow over the wings and their influence upon the wake and over the tailplanes are discussed in detail. Finally, some operational limitations to the flight of such vehicles are mentioned.

Introduction

THE use of boundary-layer control (BLC) by suction through distributed perforations to delay or prevent the separation of the turbulent boundary layer has been under examination for several years. During this period, various conventional aircraft have been modified, both here and abroad, to employ this technique of BLC to attain STOL flight. From the flight tests conducted on these vehicles, several characteristic problems typical of this method of increasing life have become apparent.

The present report is intended to summarize some of these findings and to describe the methods or approaches used to alleviate or to avoid the particular problems. Flight test results from a number of aircraft using suction boundary-layer control for lift augmentation are examined and compared.

Description of Some Aircraft Using Suction Boundary-Layer Control

TG3-A Sailplane

Extensive experimental flight research has been conducted since 1952 at Mississippi State University using a TG3-A sailplane (Fig. 1). The primary objective of this research has been the study of the properties of the turbulent boundary layer and the influence upon these properties of suction through distributed rows of perforations in the wings of the aircraft. Though obviously not an STOL aircraft, the TG3-A has been flown at relatively high angles of attack with respect to conventional aircraft without such high-lift devices, and much of the information concerning the boundary layer under these conditions is pertinent to the general problem of STOL flight.[1]

A diagram of the boundary-layer control system used on this aircraft is shown in Fig. 2. The electrical energy required for the operation of the axial flow pumps was originally supplied by a 24-v, 35-amp-hr aircraft storage battery. Subsequently the energy was supplied by a small gasoline-driven motor-generator set in order that longer periods of flight test under continuous operation could be obtained.

Piper L-21

In order to study the effects of turbulent boundary-layer control on the STOL characteristics of a conventional liaison-type aircraft, an Army L-21 (Fig. 3) was modified in 1953 to accept a suction BLC system similar to that used in the research conducted on the TG3-A sailplane.[2] Modifications to this vehicle included the addition of a single axial-flow pump, which was belt-driven from the propeller shaft, installation of suitable ducting to conduct the air sucked from the wings to the pump, and, of course, the perforation of the upper surface of the fabric wing. A diagram of this aircraft, as modified, is shown in Fig. 4.

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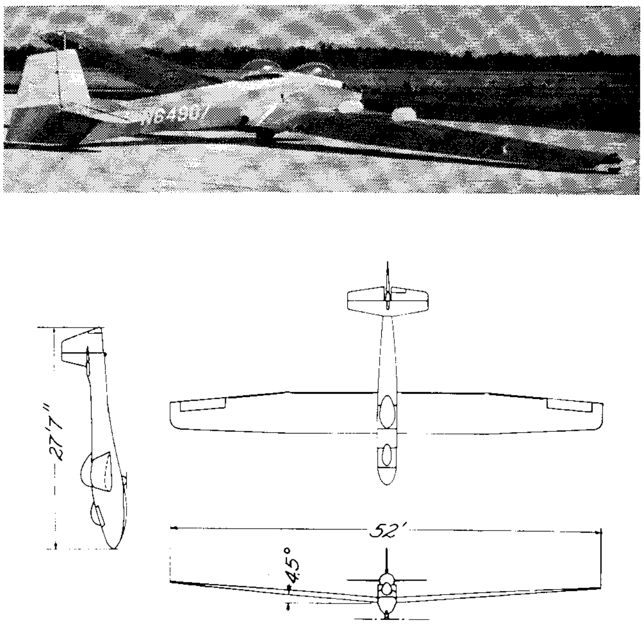

Fig. 1 Modified Schweizer TG3-A high-lift research aircraft, Mississippi State University.

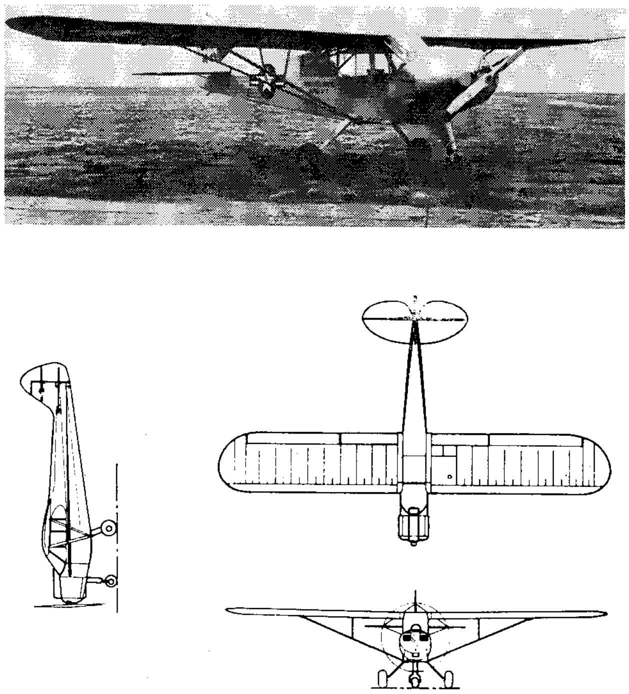

Fig. 3 Modified Piper L-21 high-lift research aircraft, Mississippi State University.

Since the suction pump in this case was mechanically connected to the engine, the amount of suction provided was dependent upon the engine throttle setting. The L-21, therefore, was primarily useful for study of takeoff characteristics since, during landings, the throttle was necessarily retarded and the BLC suction reduced accordingly.

Cessna L-19

A third aircraft used in the STOL research program at Mississippi State University was a modified Army L-19 (Fig. 5). In 1954 a boundary-layer control system similar to those used on the TG3-A and the L-21 was installed together with pertinent modifications suggested by the previous research.[3] Two hydraulically driven axial-flow pumps were fitted to the airplane, one under each wing, and the power from these pumps was taken from a hydraulic pump attached to the engine. In this case, the power for BLC could be varied by the pilot independent, within limitations, of the engine speed. The system was arranged so that full power was available to the pumps even at idling engine speeds. In this manner, the system could be utilized during landings as well as takeoffs. The details of this system are shown in Fig. 6.

In the course of the research on this vehicle, it became necessary to modify the shape and size of the vertical fin and rudder as well as the geometry of the flaps. The details of the flap modifications are discussed in this report.

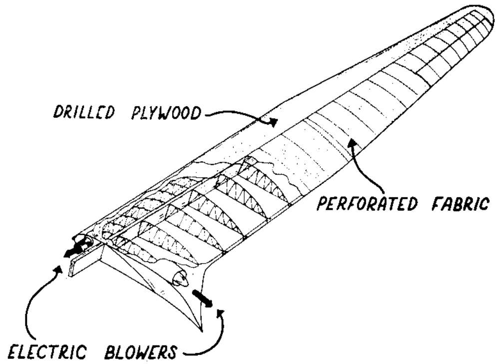

Fig. 2 Modified Schweizer TG3-A.

Army XAZ-1

The accumulated information obtained from the STOL flight research program was used to design an experimental vehicle, the MARVELETTE, later designated Army XAZ-1 (Fig. 7). This vehicle, first flown in 1963, is intended to examine the interactions and effects of the various modifications suggested by the previous research.[4-6] In particular it will be used to evaluate the effectiveness for use with boundary-layer control by suction through distributed perforations of a variable camber flap system. This flap system, which stemmed mainly from the research on the L-19, is designed to provide a large radius of curvature at the wing-flap intersection and is, in fact, a continuous surface that bends to form a deflected flap. A schematic diagram of the entire aircraft is presented in Fig. 8, and some details of the flap system are shown in Fig. 9.

The power for the BLC system on this vehicle is obtained from a constant speed, belt-driven pulley system attached to the propeller shaft. As in the L-19, full power is available to the BLC pumps over a wide range of engine speeds, although the power cannot be varied by the pilot. This aircraft is also equipped with a ducted propeller to provide increased thrust for higher acceleration during takeoff. The propeller duct also serves as both the horizontal and vertical stabilizers, and the elevator and rudder surfaces are built into the trailing edge of the duct.

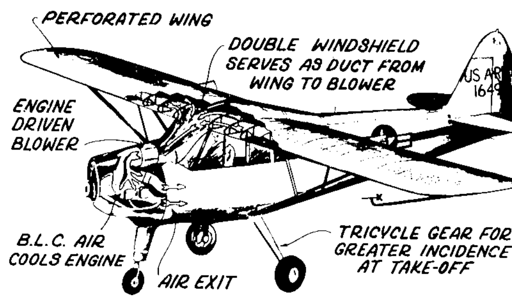

Fig. 4 Modified Piper L-21.

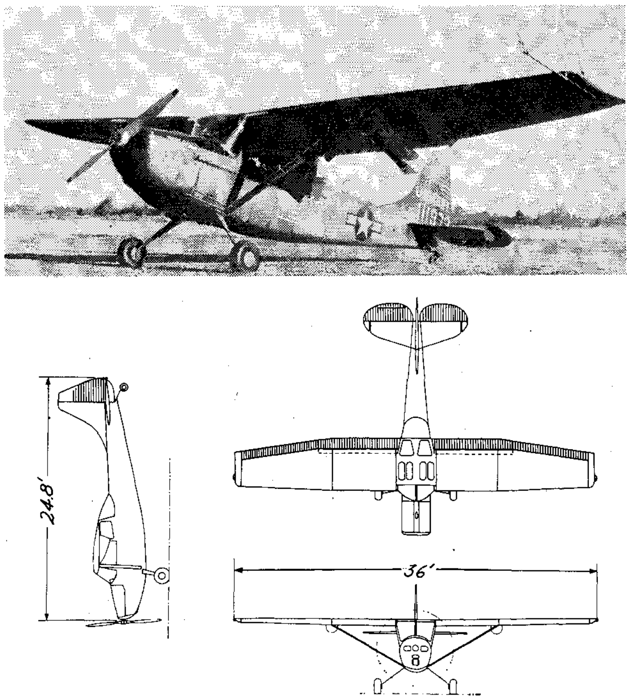

Fig. 5 Modified Cessna L-19 high-lift research aircraft, Mississippi State University.

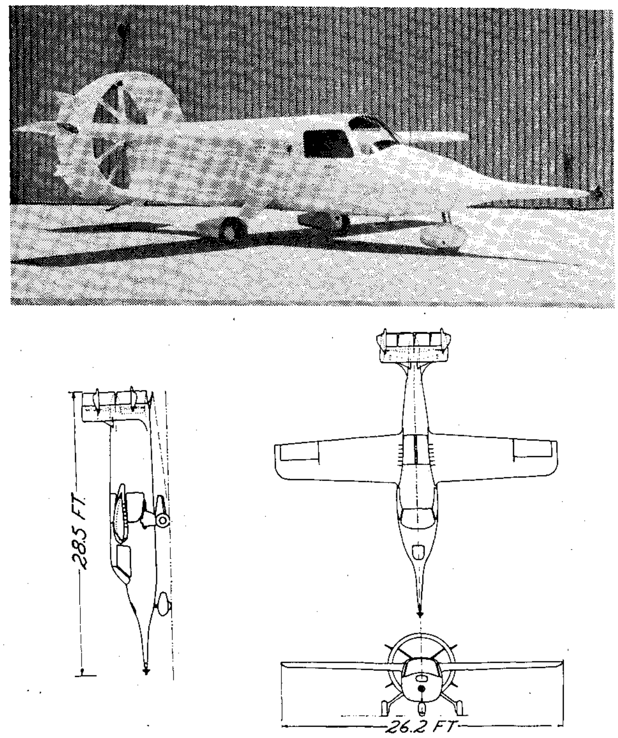

Fig. 7 MARVELETTE XAZ-1 high-lift research aircraft, Mississippi State University.

Auster MA-4

Of the work done abroad in the field of boundary-layer control by suction through distributed perforations, that done at Cambridge University in England is undoubtedly the most extensive.[7] The Auster MA-4 (Fig. 10) used in this research and first flown in 1961 is similar in many respects to the vehicles described previously. Suction power is provided by an independent gas-turbine engine ducted to the wings that are constructed so as to allow a wide and easily changed variation of the distribution of the rows of perforations. Other rather extensive modifications to the original Auster MA-4, including droopable ailerons and high-deflection flaps, were made to the aircraft.

The MA-4 is intended primarily to serve as a test bed to determine optimum techniques for controlling the growth of the turbulent boundary layer rather than to study the problems of STOL flight. However, many of the problems encountered during the flight tests of this aircraft are pertinent to the subject of STOL flight.

Fokker S-12

A considerable amount of research concerning the prevention of the separation of the turbulent boundary layer by suction is presently being conducted by the University of Delft in Holland.[8] In connection with this research, a Fokker S-12 aircraft (Fig. 11) has been modified for suction through distributed perforations. The power for suction is supplied, as in the case of the Auster, by a relatively small gas turbine, which can be controlled by the pilot to vary the amount of suction. In addition to the modifications for the suction system, the radius of the leading edge of the wing was increased to delay the separation of the flow in this region.

Although this aircraft has not been flown with the BLC system operative, extensive wind-tunnel and flight tests have indicated a number of problems related to STOL flight.

Dornier DO-27

This aircraft (Fig. 12), already capable of STOL flight, was modified by the Aerodynamischen Versuchanstalt zu Gottingen in Germany for further research on turbulent boundary-layer separation by suction.[9] The original airfoil of the DO-27 was modified by the addition of a slot near the leading edge of the airfoil. The slot thus formed was perforated for suction boundary-layer control. The suction source in this case was an independently driven centrifugal pump mounted aft of the cabin as shown in Fig. 13.

The extent of the perforated area of the wings of this vehicle was considerably less than those of the previously described airplanes. Much of the background research that led

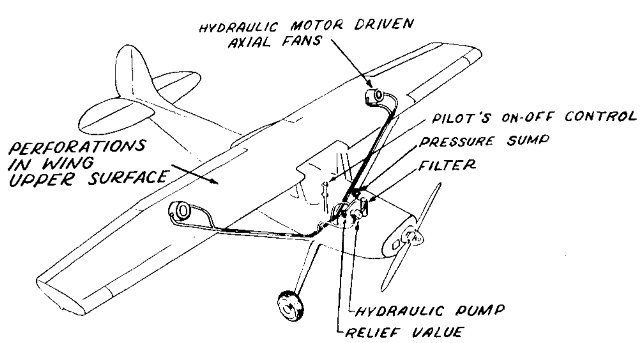

Fig. 6 Modified Cessna L-19.

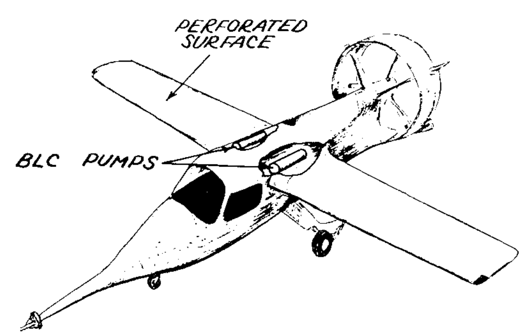

Fig. 8 MARVELETTE XAZ-1.

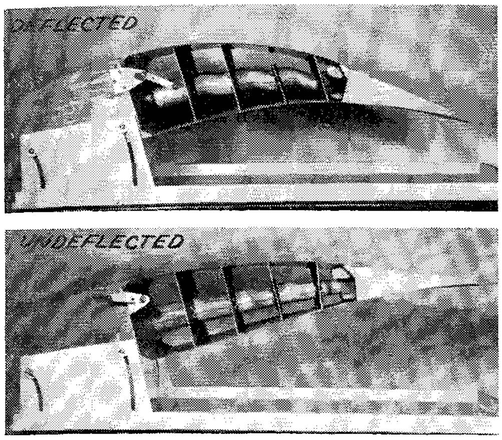

Fig. 9 Wing chamber mechanism on XAZ-1.

to the modifications of the DO-27 was conducted by the AVA on a unique airplane, the RW 3a (Fig. 14). In this research also, the suction was concentrated in relatively narrow bands of perforations near the leading edge and near the maximum thickness of the airfoil rather than being distributed over the entire upper surface as in the other cases.

Some Problems Encountered with Suction High-lift Systems

Design of Suction System

The techniques used at Mississippi State University to compute the required suction and its distribution along the chord of the aircraft wing are explained in detail in Ref. 3. It has been shown that this method and, in general, those used at other research establishments are sufficiently adequate to allow appreciable increases in the maximum airplane lift coefficient. For example, results that have been obtained with suction boundary-layer control are shown in Table 1.

It has been found, however, that it is seldom possible to calculate a priori the suction required to yield a lift coefficient considerably higher than that obtained from the wing in the original condition. Almost inevitably the need for some degree of local "doctoring" of the perforations is necessary to obtain significant lift increases. Several factors contribute to this shortcoming of methods developed so far. Of perhaps the greatest importance is the lack of basic knowledge of the behavior of the turbulent boundary layer, especially the shearing forces at the surface, under suction. Another difficulty is the disagreement between the velocity distributions predicted by potential flow theories and those determined experimentally. It is generally assumed with good accuracy that, when the flow over the surface is not separated and when the boundary layer is relatively thin, potential flow calculations can be used to determine local velocities over the airfoil. At high angles of attack, particularly for airfoils

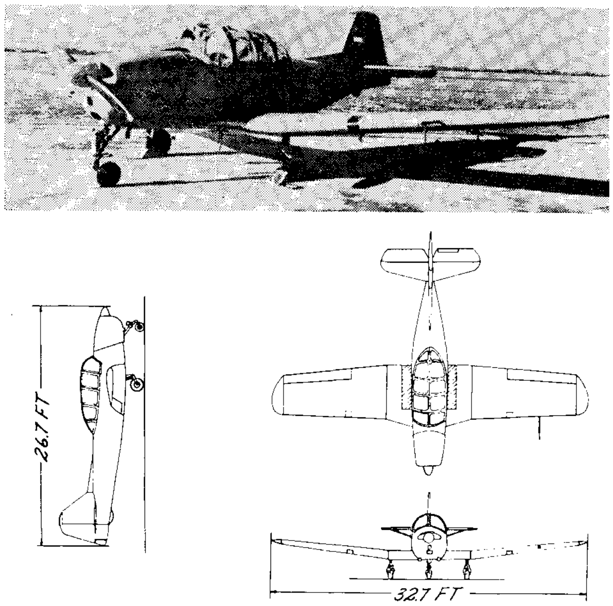

Fig. 11 Modified Fokker S-12 high-lift research aircraft, University of Delft, Holland.

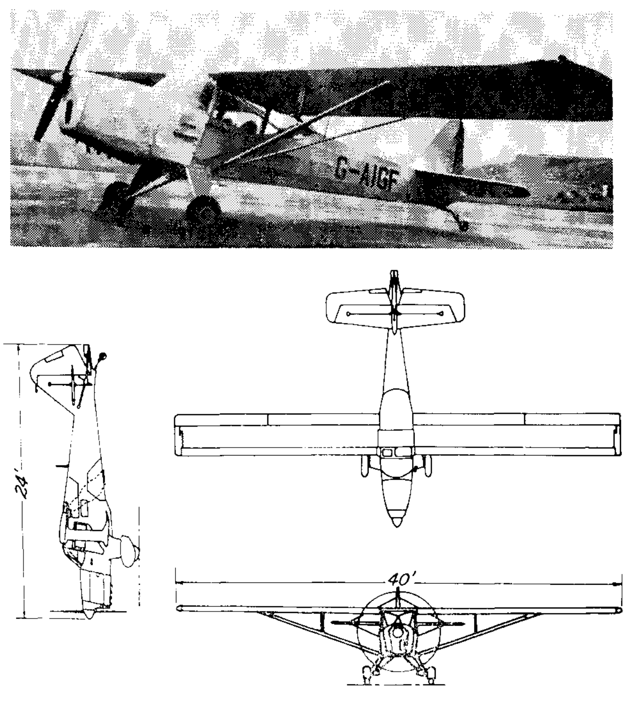

Fig. 10 Modified Auster MA-4 high-lift research aircraft, Cambridge, England.

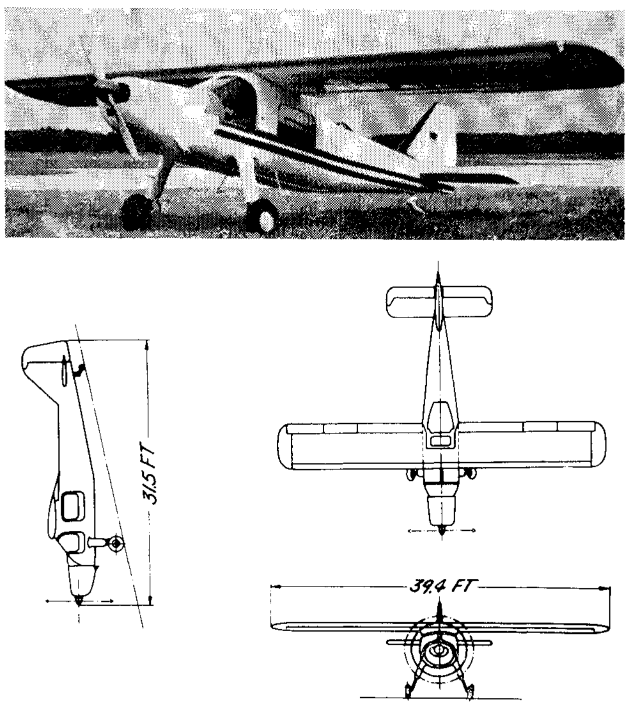

Fig. 12 Modified Dornier DO-27 high-lift research aircraft Aerodynamischen Versuchsanstalt, Göttingen, Germany.

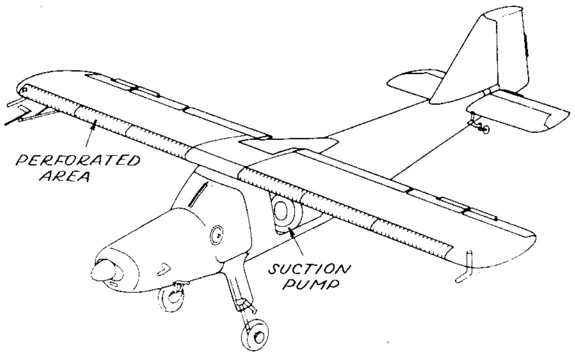

Fig. 13 Modified DO-27.

that have high-pressure peaks near the leading edge, this assumption is no longer adequate to determine the velocity distribution in that region. Furthermore, three-dimensional effects at very high lift coefficients further render the assumptions invalid. The use of the von Karman momentum equation as written in Ref. 3 assumes that the suction is continuously distributed over the surface, although not necessarily of the same intensity at each chordwise position on the wing. Continuous porosity can be closely approximated by covering the surface with such materials as scintered metals, compressed multiple layers of screen wire, or unsealed cloth or porous paper. Discrete rows of perforations do not approach a continuous porosity, obviously, unless the rows of holes and the holes in each row are very close together. It has been found that holes approximately 0.020–0.030 in. in diameter, spaced 0.10 in. apart in each spanwise row, will approximate a continuously porous surface if the rows of holes are spaced no further apart in the chordwise direction than the local boundary-layer thickness.

The efforts at the AVA have been directed mainly toward locating the position on the wing at which the boundary layer is most favorably responsive to suction, and in this case there is no assumption of continuous porosity since the suction is concentrated at that point, usually somewhere near the leading edge.

At Cambridge University, a compromise between discrete suction at a single point and continuous suction all along the chord is being examined. The suction areas on the wing of the Auster are concentrated in a number of bands of perforations distributed along the chord of the airfoil.

The effect of these methods is generally the same, although in general more suction quantity is required for the same over-all effect as the suction is concentrated into more discrete areas. Moreover, it has been shown that the porosity characteristics of the perforations depend to some extent upon the characteristics of the boundary layer at the surface. Since these two factors are mutually interactive, it is difficult to prescribe in advance just what porosity will produce the required suction.

These difficulties, which can be overcome with a minimum of additional flight tests, are perhaps of secondary importance when compared with other problems that arise when the suction is applied to conventional airplane configurations.

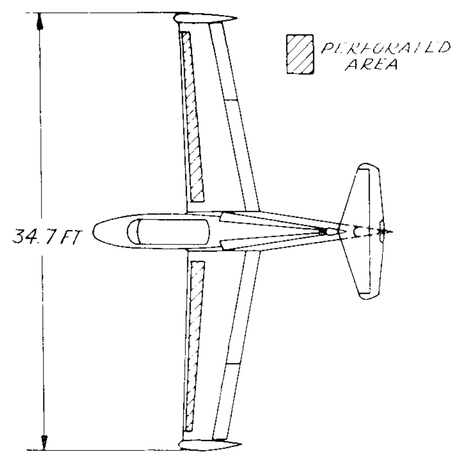

Fig. 14 RW3a high-lift research aircraft, Aerodynamischen Versuchsanstalt, Göttingen, Germany.

Installation of Suction System and Perforation of Wings

Once the suction system has been designed, it remains to actually perforate the wing and to provide the necessary amount of suction. The drilling and punching of literally millions of holes in an aircraft wing present a formidable task if the proper equipment is not available, so two machines were developed at Mississippi State University to automatically drill holes at the rate of 5 holes/sec in 0.030-in. Alclad. This machine was duplicated in Holland and is being used on the Fokker S-12. The English have also developed an automatic system although the Auster has been perforated by hand. An automatic device was built by the Germans which drills holes at the rate of about 2 holes/sec.

The pumps used to provide suction may be powered from either the main powerplant or by some auxiliary power source. The L-19, the L-21, and the XAZ-1 take the suction power directly from the engine; in the other vehicles, the suction power is obtained from auxiliary power units mounted inside the fuselage.

The major problem involved in the installation of the suction is the ducting of the air from the wings to the pump. In all of the cases cited, the interior of the wings was used as ducts and in some cases it was necessary to remove such obstacles as gas tanks to allow an unrestricted flow. The provision of separate, internal ducts within the wings, in general, results in large pressure drops and greatly increases the power required of the suction system. Experiments were conducted at Mississippi State University on a test specimen of the Fairchild C-123 wing in which the corrugated stiffeners beneath the outer skin were used as ducts for the removed air. The power required to move the air through these ducts was an order of magnitude greater than the power required to effect the required suction at the surface.

It appears, therefore, that suction through distributed perforations will be mostly restricted to aircraft with rather thick, open wing sections if power economy is a design criterion.

Effects of Weathering on Porosity

The clogging of the perforations in the wings of aircraft fitted with this type of boundary-layer control system has often been the subject of criticism of the method. Actually, however, experience has revealed that the problem of hole stoppage is of minor significance. The Piper L-21 was purposely left uncovered and untended in this regard for a period of about three years. Its original maximum lift coefficient of 4.0 was only reduced to 3.9 during this period despite the fact that accumulated dust, often wet down by showers, had been

Table 1

Aircraft	Power	Flaps, deg	Airplane C_L max
Cessna L-19	Full	45	5.2
	Idle	45	4.9
Piper L-21	Full	45	4.0
Auster MA-4	Full	0	3.4
Dornier DO-27	Full	45	2.65
Schweizer TG3-A	None	0	2.3

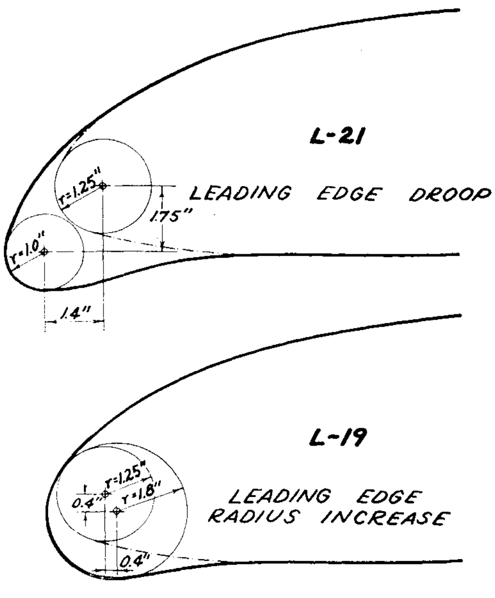

Fig. 15 Leading edge modifications.

deposited upon the fabric-covered wings.[10] The Schweizer TG3-A has been flown continually for a period of more than 10 years without noticeable adverse effects. The wings of this vehicle were, however, covered while on the ground. No serious effects have been mentioned by the workers in England, Holland, or Germany during discussions of this subject. In aircraft with metal-covered wings, the effects are even less noticeable.

The stoppage of the holes while exposed to rain is more pronounced. Upon several occasions, the L-19 has been deliberately flown in rain showers and there is approximately a 10% reduction in suction effectiveness, the effect being more pronounced with the system operating on the ground than during flight. Operational vehicles that are to be regularly exposed to such conditions should be provided with some means of draining the accumulated water from inside the wings. During a 1-hr exposure, the L-19 accumulated about 2 pints of rainwater inside each wing.

Mud thrown onto the wings during landings and takeoffs on wet ground, obviously, does completely close the holes beneath it, and the decision to use boundary-layer control on vehicles often exposed to such conditions should take account of this possibility.

Flow Separation at the Leading Edge

The technique of boundary-layer control by suction through perforations distributed on the upper surface of the wing is intended to delay or prevent the separation of the turbulent boundary layer. If the system is effective in delaying the separation of the turbulent boundary layer, the angle of attack can be increased and the airfoil can develop a higher lift coefficient. At high angles of attack, most airfoils develop a very strong adverse pressure gradient at or immediately downstream of the leading edge. If the boundary layer in this vicinity is still in the laminar state (being near the leading edge as it usually is), there exists a strong possibility that laminar separation will occur. This type of separation results in an abrupt stall without warning, a condition that is very undesirable for aircraft operating under STOL conditions. Unfortunately, this laminar separation almost inevitably occurs as the turbulent separation is delayed. The TG3-A, which utilizes a NACA 4415 airfoil section, developed a laminar "bubble" at the 2–4% chord station when the lift coefficient had been increased to about 2.0 with boundary-layer control. The "bursting" of the laminar bubble causes the airplane to stall at its maximum lift coefficient of 2.3.

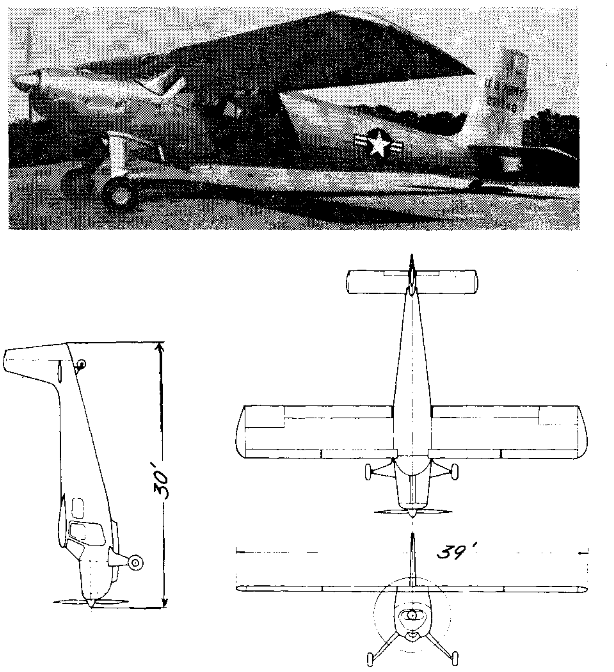

Fig. 16 Helioplane YL-24 high-lift research aircraft.

Similar situations existed on the L-21, the L-19, and the MA-4. Various modifications were made to the leading edge configurations of these vehicles in order to delay the occurrence of this separation. The first attempts in this regard on the L-21 were to use a "droop-snoot" at the leading edge by greatly increasing the camber in that region as shown in Fig. 15. This modification was only moderately successful in that it allowed only a slight increase in maximum lift coefficient. A more effective technique, which proved to be adequate for lift coefficients above 5.0, was used on the leading edge of the L-19. In this case, the radius of the leading edge circle increased and the center was dropped until the circle was again tangent to the upper surface. It is of interest to note that at a lift coefficient of 5.0 the stagnation point on the L-19 lies at about 20–25% back on the under surface of the wing. This leading edge modification has been successfully used on the L-21, the L-19, the MA-4, and the S-12. The minimum speed of each of these aircraft is dictated by causes other than laminar separation at the leading edge.

There are also other ways to alleviate leading edge separation. The Helioplane YL-24, for example, uses a slat that extends along the entire leading edge for this purpose (Fig. 16). The slat prevents separation and the airplane is able to develop a maximum lift coefficient of more than 3.0 (Fig. 17). Leading edge separation may also be prevented by means of properly distributed suction, and the leading edge slats on an

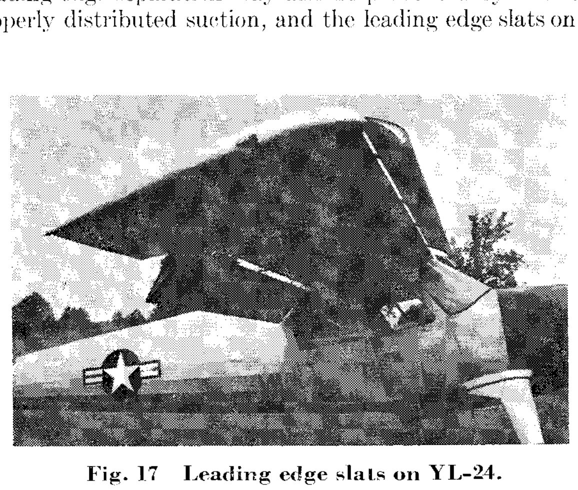

Fig. 17 Leading edge slats on YL-24.

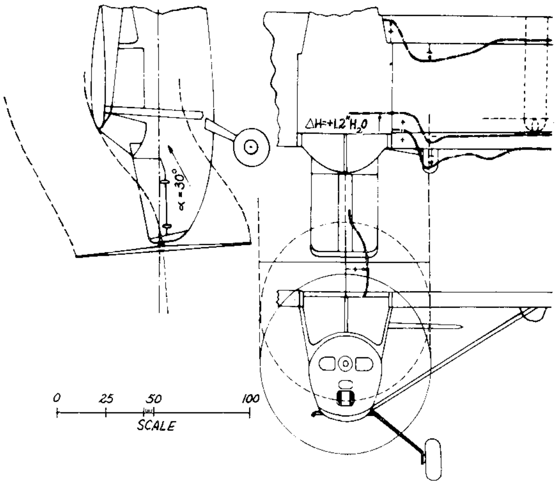

Fig. 18 Interference effects of propeller slipstream.

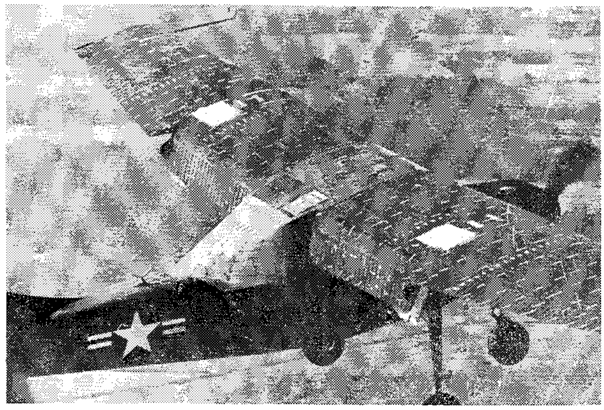

Fig. 19 Tufts showing separated flow on L-19 slotted flaps.

experimental YL-24 were replaced by a suction system utilizing rows of perforations.[11]

In any case, however, it is axiomatic that, if turbulent separation is prevented, the wing will stall as a result of separation at the leading edge. Therefore, attention should be given to this area in the design of aircraft intended to fly at the high lift coefficients made available by boundary-layer control.

Another point that should be mentioned in regard to the flow near the wing leading edge concerns the wing struts. On both the L-19 and the MA-4 there is a wing strut that is attached to the wing at approximately the 15% station on the lower surface. As mentioned previously, the stagnation streamline intersects the wing at about 20% aft on the lower surface when the aircraft is flown at high angles of attack and, in this condition, the strut interferes with the flow over the leading edge. Since the strut is aligned with the axis of the airplane, and since the local flow at high lift intersects the strut at nearly a 90° angle, a very low energy turbulent wake is shed from the strut that then passes around the leading edge and over the upper surface of the wing. The losses associated with this wake require that additional suction be applied to those areas of the wings which are immersed in the low energy flow.

The occurrence of this unexpected interference indicates that, in aircraft designed to operate at such high lift coefficients, care should be given to the location of wing struts and other protuberances not ordinarily considered as potential sources of interference.

Propeller Slipstream Interference

With the exception of the XAZ-1, the aircraft cited in this report all make use of tractor propellers, and another problem encountered during flight at high angles of attack stems from impingement of the propeller slipstream on the wing. The L-19, for example, attains an angle of attack of about 30° when flying at lift coefficients of 5.0 and above. If, in this case, the engine is running at idle or even approach power, the propeller slipstream is deflected upward and intersects the wing. It has been found that, even when the propeller is thrusting, i.e., when the total head in the slipstream is greater than that of the freestream, there exists a region around the slipstream in which there is a greatly reduced total head (Fig. 18). This sheath of low-energy air passing over the wing results in premature flow separation in that area. The quantity of suction in these regions of energy must be greatly increased if separation is to be prevented or at least kept from spreading over the entire center of the wing. The MA-4, which also flies at very high angles of attack, has experienced the same difficulty, and it has been reported that the increased leading edge radius serves to partially alleviate the problem. One phase of the research on the S-12, a low-wing aircraft, will be directed toward further examination of this phenomenon. Obviously, this problem is not restricted to aircraft using suction boundary-layer control and may be a limitation to the maximum lift attainable by wings immersed in propeller slipstreams. At the present time, the minimum velocity of the L-19 is dictated by flow separation caused by propeller slipstream interference.

Flow over Flaps and Tail Planes

The use of trailing edge flaps to increase the maximum lift coefficient of conventional aircraft wing is well known and various efficient systems have been designed. Of these systems, the single-slotted flap is perhaps most often used, and very nearly all of the high-lift aircraft mentioned in this report were originally fitted with this type of flap. Several difficulties arise, however, when using a slotted flap with a suction system in which the interior of the wing is used for ducting. Since the flap is usually a separate airfoil, hinged in some manner to the trailing edge of the wing, it is difficult to provide suction ducts to the interior of the flap. More serious than this mechanical problem, however, are the difficulties associated with the flow in and around the slot of the flap. For example, at one stage of the research conducted on the L-19, the angle of attack of that aircraft could no longer be increased because of insufficient tail power. Subsequent investigations showed that the horizontal stabilizer lay in a wake of low-energy flow, which resulted from flow separation over the flaps of the airplane (Fig. 19).

Several modifications were made to the flap system to prevent the separation of the flow over the flaps, and among these there developed a flow phenomenon that should be de-

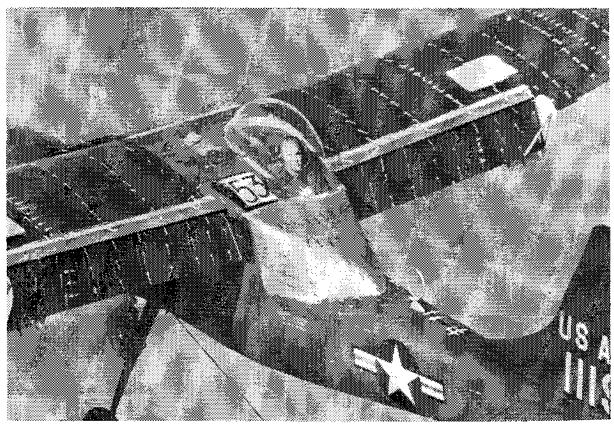

Fig. 20 Tufts showing attached flow on L-19 slotted flaps.

scribed in detail. One modification was made to the slot by closing down that portion of the trailing edge that formed the upper lip of the slot in order to narrow the slot and thereby increase the velocity of the flow through it. When observed from another aircraft it could be seen that the tufts attached to the flap indicated that there was unseparated flow over the flap (Fig. 20). Despite this, measurements at the horizontal tailplane still showed the existence of a large wake and the aircraft minimum speed remained unchanged. Finally, detailed examination of the flow in the vicinity of the slot showed that, although the flow passing through the slot remained attached to the flap, there occurred a separation of the flow in a very small area at the trailing edge of the wing which rapidly expanded into a large wake. Still further examination revealed that this separation was due to the boundary layer from the lower wing surface passing through the slot (Fig. 21). Instead of separating at point *B* as in the original case, the flow separated at point *A* giving rise to a layer of separated flow between the flow attached to the flap and the freestream flow (Fig. 22).

A similar situation was found on the French Brequet "Vultur," a low-wing, high-powered, ASW prototype that used supersonic blowing over the flaps for lift augmentation. Tufts attached to the flaps and observed from another aircraft indicated attached flow but separation from a small slat upstream caused a large wake to spread downstream and prevented the attainment of very high lift coefficients (Fig. 23).

As a result of these and other similar experiences, most of the aircraft described have made use of flaps modified to provide a continuous surface along which the controlled boundary layer on the upper surface of the wing can flow.

Even these plain flaps have the disadvantage of a relatively sharp break or at best a small flap radius at the point where the flap is attached to the wing. This small radius causes locally high velocities at the flap juncture, and the resulting high adverse pressure gradients on the flap itself require greater amounts of suction to prevent flow separation. The wings of the XAZ-1 have been designed and built such that the entire trailing edge of the wing, from 30% aft, bends downward to an effective angle of 45° and thus provides a gentle surface curvature without causing strong adverse pressure gradients.

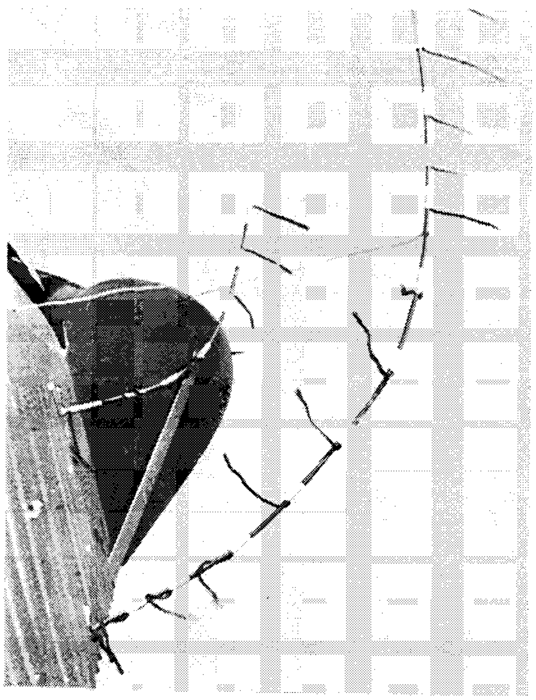

Fig. 21 Tuft rake on L-19 flap.

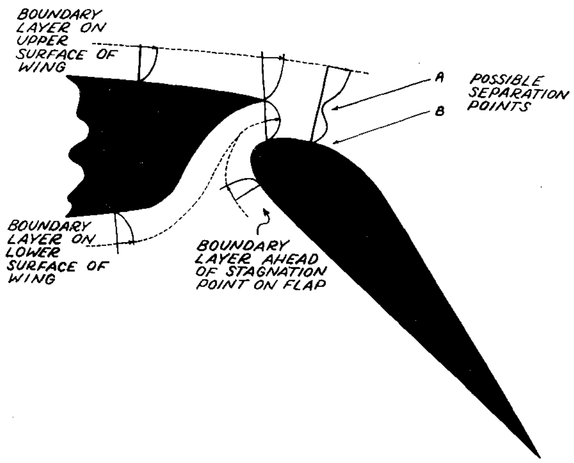

Fig. 22 Details of the flow in a slotted flap.

Operational Characteristics

Flying at the high angles of attack made possible by the boundary-layer control systems presents several special problems if full advantage is to be taken of the high-lift characteristics of the aircraft. In takeoff, for example, it is desirable that the aircraft landing gear allow the airplane to achieve a high angle of attack so that a high lift coefficient can be developed. The conventional landing gear consisting of two main wheels and a tail wheel, which is the type originally used on most of the aircraft described herein, does not allow the aircraft to closely approach its maximum attainable lift coefficient while on the ground. For this reason, most of the aircraft tested at Mississippi State University were converted to tricycle-type landing gear at some stage of their modification. Since the main wheels of the tricycle gear are much further aft than the conventional gear, the angle through which the aircraft can be rotated during takeoff is greatly increased, thus allowing the utilization of higher lift coefficients for takeoff.

The tricycle gear also has good characteristics for landing at high lift coefficients. In this condition, the main wheels usually touch down first, since the aircraft approaches the ground at a rather high nose-up attitude. At touch down, the fuselage rotates forward and reduces the angle of attack thereby decreasing the lift and allowing greater braking from the main wheels and steering from the nose wheel.

The landing approach at high lift coefficients presents other difficulties resulting mainly from the very high induced drag of the wing under these conditions. In most instances the aircraft operate on the "back side" of the power required curves during low-speed approaches, i.e., further decreases in speed either increase the sinking speed or require additional

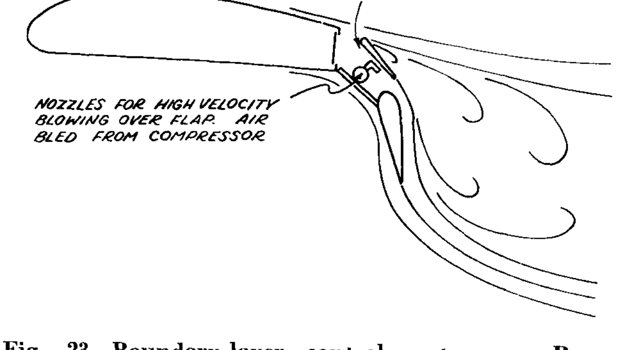

Fig. 23 Boundary-layer control system on Brequet "Vultur."

power. The modified L-21, for example, could not maintain level flight at minimum speed even with full power and was therefore power limited in takeoff in that it was unable to utilize the full lift coefficient that could be developed by the wing. Landings at the highest lift coefficients could be accomplished satisfactorily in the L-21 in calm air since the sink speed at these velocities was not large. However, flight at high lift coefficients in gusty air was, at best, difficult. Because of the steepness of the power required curve at low speeds, small gust velocities produced rather large changes in rate of climb or sink. This same effect was very pronounced in the modified L-19 at lift coefficients above 4.0. As a result, pilots were reluctant to approach at lift coefficients much in excess of 3.5.

The effects on the tailplanes of the high down-wash from the wings vary considerably on these high-lift aircraft. A deflection of the flaps, at high lift coefficients, on the L-21 and the Cambridge MA-4, produces a marked nose-up pitching movement.

The modified L-19 exhibits a very nearly neutral trim change when flaps are deflected, whereas the MARVELETTE XAZ-1 tends to pitch down with increases in flap deflection. The accurate prediction of this characteristic is particularly difficult, if at all possible, because of the lack of present knowledge concerning the down-wash pattern behind the wing and the influence of the wing wake upon this pattern.

Concluding Remarks

High maximum lift coefficients for STOL flight have been attained by a number of aircraft using boundary-layer control by suction through distributed perforations. The attainment and utilization of these high lift coefficients have emphasized several shortcomings of currently used aerodynamic theories and have brought into prominence the interference effects of some aircraft components not ordinarily considered at relatively low lift coefficients.

1) The velocity distribution around an airfoil as determined by potential flow techniques is not sufficiently accurate at high lift coefficients even when the boundary layer is kept thin by suction. Especially at the airfoil leading edge, where high-pressure peaks generally occur, the theories fail to predict the actual velocities with sufficient accuracy. Furthermore, the present knowledge concerning the surface shearing effects of the turbulent boundary layer with suction is sufficient to accurately predict the effects of suction on the development of the turbulent boundary layer on a wing at high lift coefficients. However, an effective distribution of suction can be determined by the use of these theories if the theoretical analysis is supplemented by data obtained experimentally as the lift coefficient of the aircraft is progressively increased. Closely spaced rows of perforations have been shown to produce a good approximation of a continuous porosity provided the rows are no further apart than the local boundary-layer thickness.

2) Interference effects from struts attached near the leading edge may be expected at lift coefficients of the order of 5.0, and flow separation around leading edges of even moderately thick airfoils generally occurs before this value is reached. Both of these difficulties can be relieved by increasing the leading edge radius of the wing as much as 40%.

3) The use of slotted flaps on wings with boundary-layer control through distributed perforations presents both mechanical and aerodynamic problems. The provision of ducting to the flapped areas and prevention flow of separation caused by the mixing of boundary layers can be simplified by the use of a large radius plain flap or a wing camber-change device.

4) The low-energy flow surrounding the propeller slipstream seriously interferes with the effectiveness of the boundary-layer control on high wing aircraft when the slipstream is allowed to impinge upon the wing. This interference can be circumvented by the use of a pusher propeller, and flight tests in Holland are being directed toward the examination of the possibilities of avoiding such interference by the use of a low wing design.

5) The conventional tail-wheel equipped aircraft can seldom attain the angle of attack for takeoff made possible by the use of boundary-layer control, but sufficiently high nose-up attitudes can be easily achieved with tricycle gear.

6) The effectiveness of the horizontal stabilizer is greatly influenced by its location with respect to the wake and down-wash from the wing. In many cases, the presence of the stabilizer in the low-energy wake from the wing may limit its ability to produce sufficient nose-up pitching moment to approach the maximum lift coefficient available from the wing. The down-wash from the wing may also produce an undesirably strong nose-up pitching moment when flaps are deflected. The use of a T-tail well removed from such influences may reduce these tendencies.

7) The very high induced drag associated with the lift coefficients made possible by boundary-layer control gives rise to control difficulties during landings and takeoffs at low speed, especially in gusty air. At present, this is probably the most serious problem associated with high lift STOL aircraft.

It should be remarked, in conclusion, that the difficulties outlined previously have been isolated and in some cases resolved as a result of continued, simultaneous flight research programs both here and abroad. These programs have indicated the need for further research in many areas considered sufficiently well explored for conventional flight. The application of further research in these fields is pertinent not only to aircraft utilizing suction boundary-layer control, but also to other types, such as those using tilt wings and deflected slipstreams, where unusual flow patterns can be expected.

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