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Flight Experiments on Suction for High Lift

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A single-engined light aircraft has been modified by fitting new wings and a suction unit driven by a small gas turbine. By applying suction through perforations in the leading edge of the wing and at isolated strips along the upper surface, and by modifying the leading-edge geometry, the stalling C_L without flap and with power on has been raised from 1.6 to a maximum of 5.3. With flap 30°, values of approximately 6 have been recorded. Over-all suction quantity coefficients are in the range 0.008 to approximately 0.01, and the stall from angles of attack as high as 42°, suction on, is more pleasant than the normal stall, with only a small loss in height. The maximum measured section lift coefficient, outside the slipstream and without flap, is approximately 4. A calculation method has been developed for the turbulent boundary layer with suction or blowing, which indicates lower suction requirements than have been necessary so far.

1. Introduction

OVER the past ten years or so boundary-layer control by blowing has received an increasing measure of acceptance and for certain applications, perhaps the most urgent, its advantages over suction are readily apparent; the availability of high-pressure air for blowing, the restriction on duct area imposed by thin wings, and the very high suction peaks occurring on such wings, all combine to make blowing the obvious means of boundary-layer control for improving the low-speed characteristics of really high-speed aircraft. There remains, however, the category of STOL aircraft, propeller driven and with relatively thick wings, where suction is likely to prove more economical and possibly no less convenient; there also remains an intermediate range of aircraft where the issue can only be decided when more comprehensive and systematic experimental data are available and a satisfactory design procedure has been evolved. It was with these considerations in mind that the present investigation at Cambridge was undertaken.

Numerous investigations have been performed in the past and a fairly comprehensive review of this work up to 1960 is given in Ref. 1. Since then there have been the wind-tunnel and flight experiments of Schwarz and Wuest[2,3] in Germany which are of considerable interest, but somewhat limited scope.

The experiments of Raspet and Cornish[4,5] at Mississippi during the period 1950–1955, which receive only passing mention in Ref. 1, showed most convincingly what could be accomplished by applying suction to a light aircraft. In their later experiments the maximum lift coefficient of the Cessna L 19 aircraft had been raised to values above 5 by the use of very modest suction powers and only a minimum of modification to the basic aircraft. It was therefore decided to carry out similar experiments at Cambridge, again using a light aircraft, but with the emphasis on obtaining detailed measurements at high lift coefficients and some insight into the factors governing the design of suction aerofoils rather than on using suction to improve the landing or take-off performance of the particular aircraft used. As compared with wind-tunnel tests, the flight experiments offered the advantages of an absence of tunnel constraint, the ability to assess stalling behavior and handling problems at the stall, and the acquaintance with any practical difficulties that might arise in the design, maintenance, and operation of a suction wing.

The flight results alone would obviously cover only a narrow range of conditions, and to fit them into a general picture it seemed essential to develop an acceptably reliable method for calculating the turbulent boundary layer with suction so that a variety of different Reynolds numbers and pressure distributions could be covered. In addition, it seemed desirable to show the sort of gains in landing and take-off performance which would follow from the ability to achieve high lift with negligible penalties in profile drag. In this paper the aircraft and the flight experiments to date are discussed first, then other aspects of the investigation are briefly outlined.

Presented as Preprint 65-750 at the AIAA/RAeS/JSASS Aircraft Design and Technology Meeting, November 15–18, 1965, Los Angeles, Calif.; submitted December 9, 1965; revision received August 4, 1966. The authors record with regret that since this paper was written the aircraft has crashed, with the loss of life of the pilot, Mr. B. Wass, and the flight observer, Mr. R. Krishnamurthy, whose name appears in the text. The cause of the accident, which occurred from a substantial altitude, has not been established. [3.01, 7.05]

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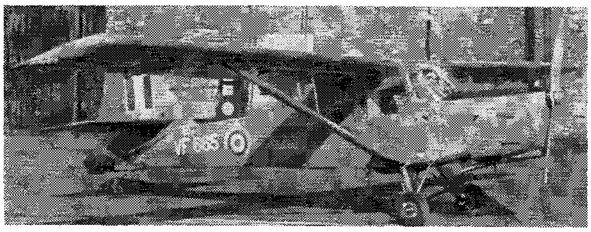


Fig. 1 Aircraft as originally accepted.

2. The Aircraft

2.1 General

The experimental aircraft is a greatly modified Auster Mk7 with only the engine and the fuselage structure (extensively reinforced) remaining from the original aircraft. As the scheme was first conceived, the only major modifications envisaged were 1) the building of new wings of somewhat higher aspect ratio and 2) the fitting of a suction plant in the fuselage; the latter would replace the third person, usually carried. In the design stages, however, the simplicity of the original conception was lost and the performance of the aircraft deteriorated markedly as a result of increased AUW and, more important, increased drag. The aircraft was taken over by the University in the form shown in Fig. 1; but, before starting the experiments, it seemed essential to bring its performance up to a more acceptable level. The initial rate of climb had been somewhat improved by fitting a larger diameter, lower pitch airscrew, but much more substantial gains were achieved by an extensive drag cleanup. Figure 2 shows zero-thrust drag polars measured before and after this operation, and Fig. 3 shows the envelopes of numerous timed climbs. The aircraft is shown in Figs. 4 and 5 in its final form (Table 1).

The following sections describe the suction system, the wing construction, and the instrumentation. The only other special feature worth mentioning here is the variable-incidence tailplane, servodyne operated from a hydraulic accumulator which also operates the flaps; pressure in the accumulator is maintained by a hand pump.

2.2 Suction System

The suction flow from the wings first passes to the center section where turning vanes deflect it rearward. A further set of turning vanes then directs the flow downward toward the suction unit to which it passes via a short duct incorporating a variable bleed; this is controlled by the observer who sits facing aft. The arrangement is shown in Fig. 6.

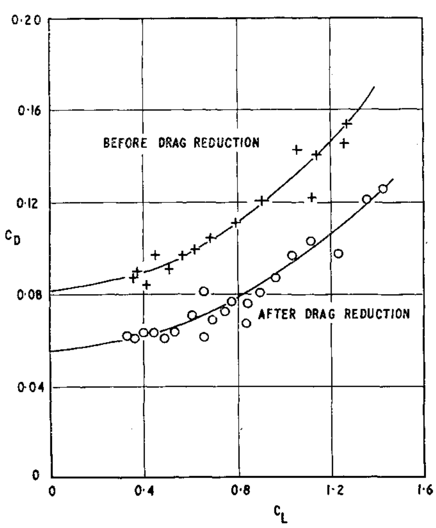


Fig. 2 Zero-thrust drag polars.

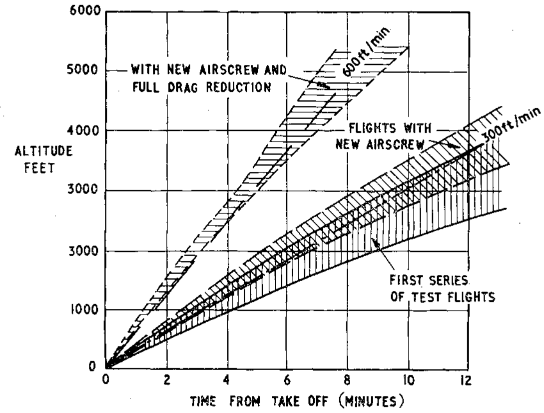


Fig. 3 Envelopes of timed climbs.

As will be seen from Fig. 7, the suction unit itself‡ consists of a small commercial gas turbine nominally rated at 60 brake horsepower (BHP), which drives an axial-flow fan via a centrifugal clutch and an epicyclic reduction gear. Maximum fan rpm is 9500, which corresponds to a turbine speed of approximately 45,000 rpm. This maintains a 1 psi reduction of pressure in the main ducting for a flow in the region of 85 ft^3/sec. Thus the maximum effective air horsepower is approximately 22. It is only recently that the unit has been cleared to a fan rpm of 9500; earlier, the maximum permitted was 8700. The unit is started on the ground by means of a heavyduty electric drill, and is controlled in the air by the observer. Sufficient fuel is carried for approximately 50 minutes operation.

2.3 Wings

These are of two-spar all wood construction with normal truss ribs, and flaps and ailerons piano-hinged to the lower surface. The interspar space provides the main duct, which communicates with the leading-edge section, and flaps and ailerons via orifices in front and rear spars. The upper surface of the wing is of sandwich construction, and suction can be applied more or less continuously around the wing leading edge and nose of the flap, as well as at seven spanwise strips along the upper surface. In these regions the outer surface

Table 1 Leading particulars of high-lift research aircraft

Wing	
Area	160 ft^2
Span	40 ft
Aspect ratio	10
Chord	4 ft (const)
Section	NACA 23015 (modified)
Dihedral	+1°
Constant incidence	(3° to fuselage datum)
Flap and aileron hinge	at 73%C
Weight	
Fully loaded	2900 lb
Minus fuel	29750 lb
Power	
"Gypsy Major" VII	135 BHP
Airscrew	
"Fairey Reed" (metal) fixed pitch	
Diam	7 ft 6 in.
Pitch (nominal)	3.21 ft
Loadings[a]	
Wing loading	17.8 psf
Power loading	21.1 lb/BHP
Approx. thrust/weight ratio	0.2

[a] Based on a weight of 2850 lb.

‡ Developed by David Budworth Ltd., Harwich.

is of perforated 1 mm ply separated from the inner skin by spanwise stringers and diagonal members, which divide the space between inner and outer skins into a series of cells which communicate with the interior of the wing via small orifices fitted with simple rubber flap valves. This insures that outflow through the surface cannot take place when suction is inoperative. The outer perforated surface is covered with heavily doped tissue that is pierced by hand in regions where it is desired to apply suction. Figure 8 shows details of the wing construction.

2.4 Instrumentation

Provision is made for measuring pressure distributions around the wing at the four spanwise stations indicated in Fig. 5. Thirty static pressure tappings are incorporated at each station, and a changeover switch is fitted so that any one of these four sets of 30 pressure tappings can be connected to the manometer. The manometer itself, which is normally filled with carbon tetrachloride, has 62 tubes arranged in banks of ten with two balance tubes, so that a range of internal pressure and pitot-comb readings can be simultaneously recorded, as well as a chordwise pressure distribution. The manometer is fitted with a freezer, and the liquid levels are recorded by marking them with suitable pencil on a sheet of flexible transparent plastic. The sheet is wound on rollers clipped to the face of the manometer so that it can be wound-on to record successive sets of data. The observer, as well as the manometer, is provided with a full set of turbine instruments, an altimeter, a sensitive airspeed indicator (ASI), and an inclinometer. The last is used along with the recorded rate of climb or descent to determine the incidence.

3. Flight Experiments

3.1 Initial Tests

Flight experiments started with suction applied at the flap knuckle only. A flap angle of 30° was chosen and several flights were made with progressively increased suction. It was found that fully attached flow could be maintained over the flap at speeds above the normal stalling speed, thus giving reduced angles of attack and improved handling. The stall itself, however, was always preceded by the development of normal separated flow over the flap, and the final stalling speed of 47 knots indicated air speed (IAS) was virtually unaltered.

With small amounts of suction applied in the leading edge region, however, fully attached flow was maintained over the flap right down to the original stalling speed. The stalling speed itself was reduced from 47 to 42 kt. Again, however, the stall was preceded by full separation over the flap, and this seemed to demonstrate fairly conclusively that flap suction could have very little effect on the stalling speed although, of course, a considerable reduction in angle of attack could be obtained at speeds quite close to the stall. Since the objective at this stage was, in fact, the reduction of stalling speed, there seemed little point in continuing with flap suction. The flap knuckle was therefore sealed and subsequent experiments have all been carried out in this condition. Representative pressure distributions measured at the midflap station in these early experiments with suction applied to the flap are shown in Fig. 9.

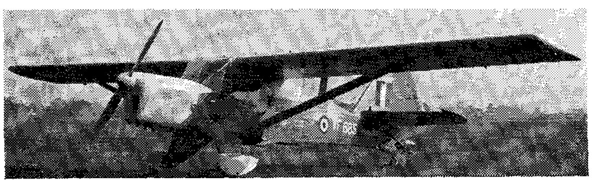


Fig. 4 Research aircraft in final form.

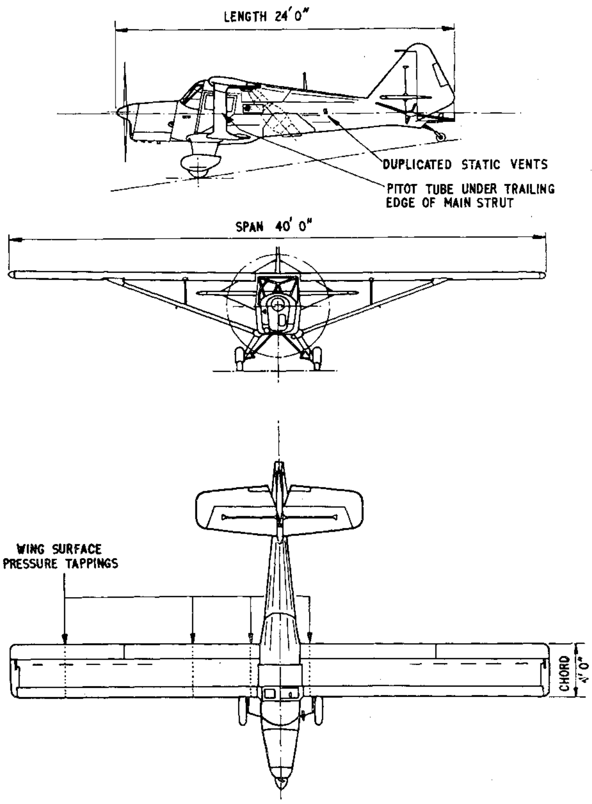


Fig. 5 General arrangement of research aircraft in final form.

With the nose of the flap sealed, a short series of flights now was carried out with progressively increased suction areas opened up around the nose and in the main wing surface. Stalling speeds were reduced to 40 kt without flap and to 38 kt with flap 30°. Corresponding C_L values were, respectively, 3.2 and 3.4 for a C_Q in the region of 0.006. The stalling speed without flap was originally 56 kt, so that $C_{L\max}$ had been approximately doubled by the application of suction.

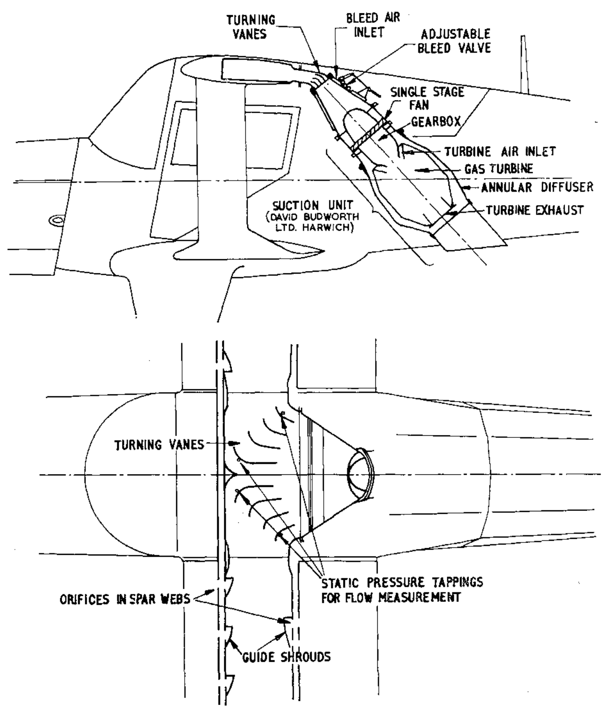


Fig. 6 Main features of suction system.

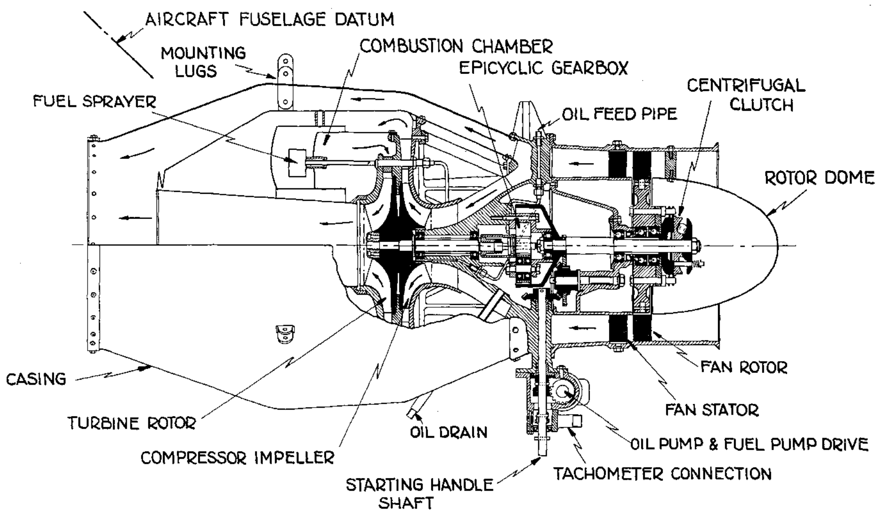


Fig. 7 Suction unit.

It should be mentioned that the stalling speeds quoted were all obtained with full or nearly full throttle. At idling or zero-thrust throttle settings, the flow, with suction applied, separated over the center section; and, with full up elevator the aircraft settled down in steady descending flight at an IAS of 50 kt.

The pressure distribution measured at the midflap section for an over-all C_L of 3.1 without flap is shown in Fig. 10a. Trailing edge pitot combs indicated fully attached flow with a boundary-layer thickness on the upper surface at the trailing edge somewhat greater than $2\frac{1}{2}$ in. The integrated pressure distribution gives a resultant force coefficient C_R of approximately 3, and, since, C_D will be small compared with C_L, this latter may be taken to have very nearly the same value as C_R.

3.2 Leading Edge Modifications

The $C_{L\max}$ values so far achieved were somewhat disappointing in view of the suction power available; and whereas some improvement might have been achieved by altering the distribution of suction, it was felt that such improvements were likely to be small. It was therefore decided to proceed, instead, with modifications to the leading edge, which the experiments of Raspet and Cornish[4] had shown to be effective. By reducing the leading-edge suction peak, which at high incidences considerably exceeded the suction available in the interior of the wing, it was hoped not only to improve conditions in the boundary layer at the beginning of suction but also to make it possible to apply suction closer to the leading edge.

The changes of contour were carried out in two stages, as shown in Fig. 11. The new shapes were obtained simply by building up the original leading edge with balsa blocks. The resulting pressure distributions are shown in Fig. 12. The first modification was a simple increase in radius, the center of curvature being chosen to give a small amount of droop. This gave a marked reduction in stalling speed, but the reduction in negative pressure peak was disappointingly small; probably because the modification gave little, if any, reduction of surface curvature in the region of peak velocity. The stalling speed, flaps up, had fallen to 38 kt (over-all C_L = 3.9), and a stalling speed with the flaps lowered 30° of 35 kt (over-all C_L = 4.6) was recorded. The pressure minimum at the leading edge, however, still exceeded the lowest suction pressure available for airspeeds below about 47 kt.

The second contour was arrived at by systematically modifying a short section of the leading edge spanning the midflap pressure tappings; pressure distributions obtained in flight were used as a guide at each step. This contour succeeded in bringing the pressure minimum within the range of the available suction pressure (see Fig. 12) and when applied over the full span, it gave a further decrease in stalling speed to 35 kt, flaps up (mean C_L = 4.6). The stalling lift coefficient, suction off, had been raised from the original value of 1.65 to 1.8 power on, flaps up.

More recently, as mentioned in Sec. 2.2, it has become possible to increase the speed of the suction unit to a fan rpm of 9500. Using the increased suction pressure that this gave, together with some small extensions of the suction area forward at the leading edge, a stalling speed, flaps up, of 32 kt

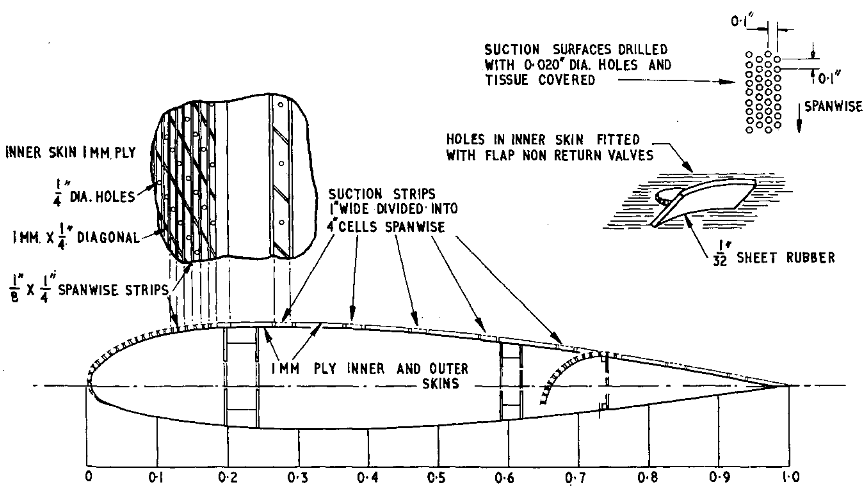


Fig. 8 Wing section showing details of section surfaces.

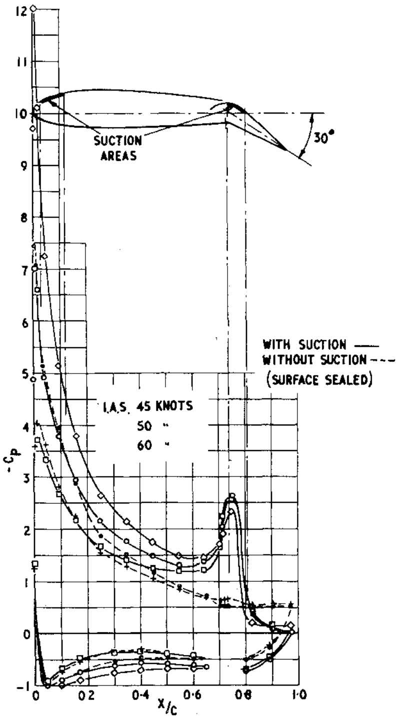


Fig. 9 Typical pressure distributions with flap suction (at mid-flap).

IAS (mean over-all C_L = 5.3 − 5.4) has been recorded with fair consistency. It now is possible, in principle, to experiment with suction round the entire leading edge at over-all lift coefficients up to the highest obtainable, though for structural reasons this may not in fact be feasible.

The over-all suction quantity coefficients for this last series of tests were in the range 0.008–0.0095, allowance being made for leakage flow which amounted to approximately 8% of the total, according to a recent calibration in the course of which the upper surface of the wing was covered with an impervious polythene sheet. The distribution of suction achieved close to the stall at the midflap section is shown in Fig. 13 along with the corresponding distributions of external velocity and pressure coefficient. The suction distribution was inferred from the pressure drop across the surface and its known resistance characteristics.

Of the IAS values quoted in this report, the later ones (following the leading-edge modifications) represent observer's ASI readings, and the earlier ones represent pilot's ASI readings. Over-all lift coefficients are based on the AUW of the aircraft at take-off, with allowance for turbine and main fuel used, a gross wing area of 160 ft^2, and ASI readings corrected for instrument and position errors. These last errors were determined by the use of a standard trailing static and a Kiel tube mounted outside the slipstream, a few inches beneath the wing at the half-chord point. The static vents used for pilot's and observer's ASI systems were apparently subject to only small errors, and the total correction to the observer's ASI readings at 31 kt (the lowest speed for which the position error has been determined) was only in the region of 1 kt. The correction to the pilot's ASI readings in the range 45–90 kt varied only from about −1 to +1 kt, but the readings became increasingly inaccurate at lower speeds.

The usual plot of pressure against chordwise distance, obtained after the second leading-edge modification, is shown in Fig. 10b for comparison with that obtained with the original leading edge at a lower lift coefficient. In addition, both chordwise and normal-to-chord plots are shown in Fig. 14§

§ These measurements were made at a lower airspeed than those shown in the corresponding figure of Ref. 17. The change in the undersurface pressure distribution and the relatively small increase in resultant force were established as being caused by the effect of the wake of the main lift strut.

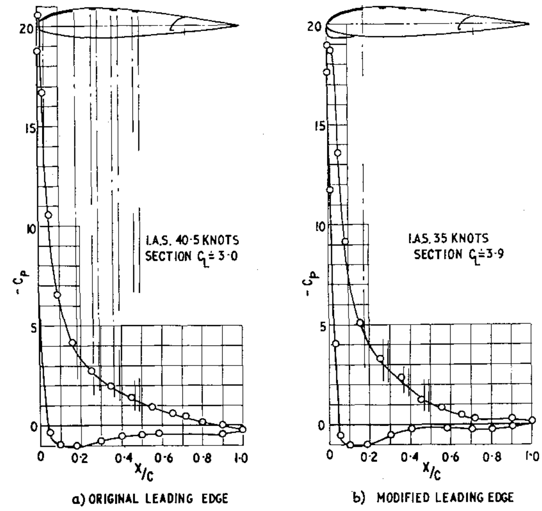


Fig. 10 Pressure distributions measured with flaps up (at midflap).

together with the vector diagram obtained from the integrated pressures. It will be seen that the chordwise force coefficient is large and quite comparable in magnitude with the normal force coefficient.

3.3 Variation of Lift Coefficient with Incidence

A comprehensive view of the results so far obtained is provided by Fig. 15,¶ which shows aircraft lift coefficient (i.e., over-all C_L) plotted as a function of incidence. It will be seen that the leading-edge modifications increase the lift-curve slope, and the effect of an increasing vertical component of the thrust is apparent at the higher incidences. The figure shows graphically the increases in $C_{L\max}$ brought about by the combination of suction and leading-edge modifications.

Slipstream effects and the vertical component of thrust are estimated to contribute approximately 24% of the total lift at an over-all C_L of 4.6. The suction unit is supplying almost direct lift at the higher angles of attack, but its thrust is only 45–50 lb at full rpm, so that its contribution at no time exceeds 1.8%.

3.4 Stall Patterns

In the course of the leading-edge modifications, checks on the stalling pattern were made using wool tufts photographed from another aircraft. The main characteristic revealed was a tendency for strongly localized separations to develop at the edges of the slipstream, as may be seen from Fig. 16, which

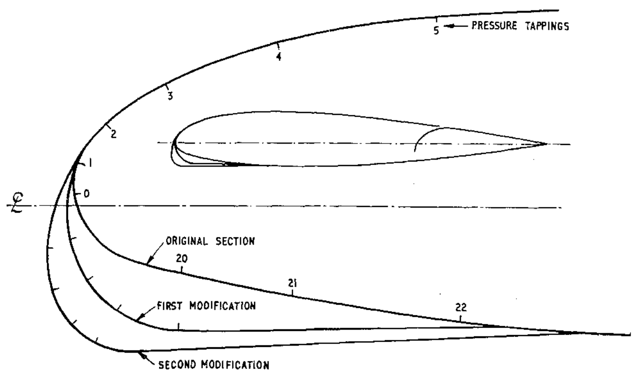


Fig. 11 Leading-edge modifications.

¶ Differences between this figure and the corresponding figure of Ref. 17 are accounted for by more comprehensive measurements of position error and the removal of the lift strut fairing which greatly improved repeatability at high lift coefficients.

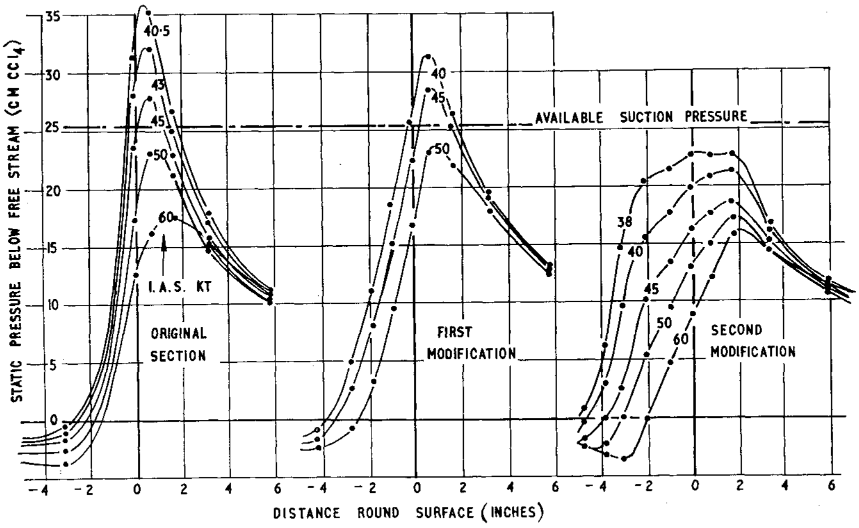


Fig. 12 Pressure distribution around original and modified leading edges.

shows the aircraft close to the stall following the first leading-edge modification. Investigations with pitot tubes in flight, and in the wind tunnel using a model airscrew, showed that at low advance ratios there was a region at the slipstream edge where the pitot pressure was not only lower than free-stream total pressure, but actually fell below freestream static pressure. It is reasonable to assume that these regions represent the paths of the airscrew-blade tip vortices.

The separations further outboard on either wing, also visible in Fig. 16, are probably caused by wakes from the lift struts being carried around over the leading edge: an effect that had been encountered earlier, like the slipstream edge effect, by Cornish.

The second leading-edge modification produced a more nearly uniform stalling pattern. Signs of local separation were much delayed and a fairly uniform trailing edge separation accompanied their appearance.

3.5 Additional Observations

The stall has been generally mild throughout, and is considerably more pleasant from a high angle of attack, suction on, than in normal flight with suction off. There is very adequate stall warning and the loss of height from an unaccelerated stall is small (of the order of 50 to 100 ft).

The stall caused by sudden loss of suction also is docile, as has been checked by shutting off the high pressure cock to the turbine and simultaneously opening the suction air bleed. The aircraft immediately pitches nose-down, and recovery is normal.

With power off and suction on the aircraft cannot be stalled in the normal way, and the application of full up elevator results in steady descending flight at an IAS of about 43 kt (C_L = 3.0). With a loading of approximately 21 lb/BHP, the aircraft is somewhat underpowered (probably grossly so by STOL standards), but level flight can be maintained up to an over-all C_L of about 4, and at the highest lift coefficients the rate of descent is less than 100 fpm.

4. Section Design

The flight experiments have shown the importance of reducing the negative pressure peak at the leading edge to a minimum if suction is to be used effectively for high lift, and the logical conclusion to this process is to maintain a uniform low pressure around the leading edge over the full depth of the section and as far back along the upper surface as possible. This could be done for a particular incidence, at least in principle, by insuring that the relevant part of the contour takes the form of a free streamline.

Although the general problem of design for free streamline flow may be somewhat intractable, it becomes comparatively simple when the contour, with the exception of the loading edge region, is specified by two straight lines. Hurley[1,6] **

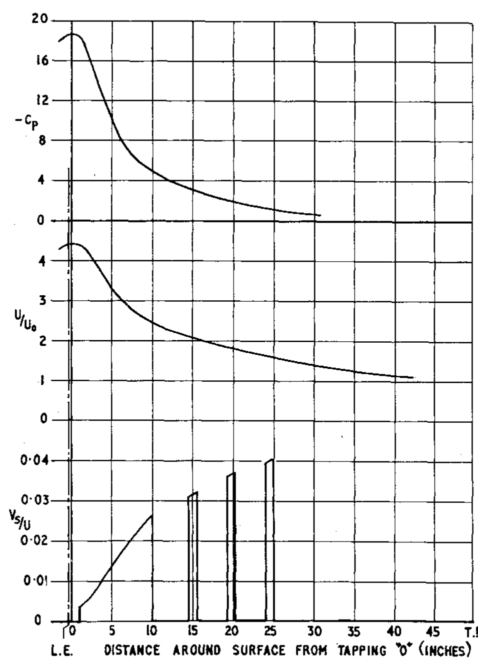


Fig. 13 Pressure, velocity, and suction distributions for section C_L = 3.9.

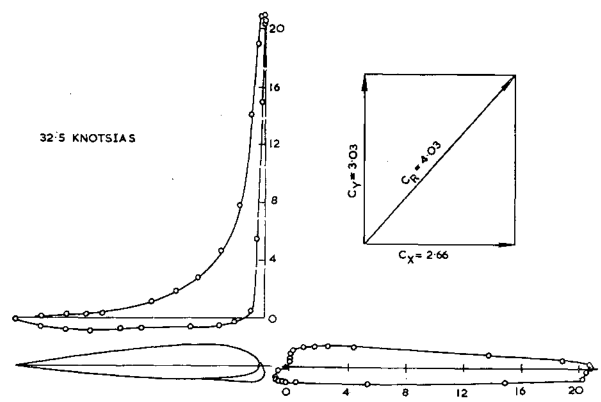


Fig. 14 Forces from integrated pressure distributions at mid-flap station.

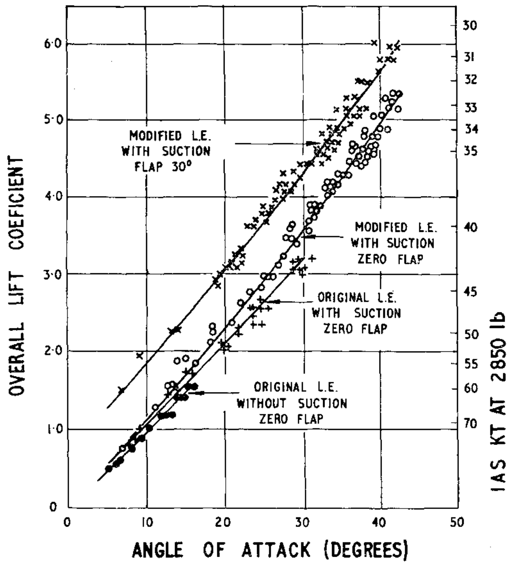


Fig. 15 C_L — α curves full throttle.

has solved this problem in quite another connection, and from an inspection of the data given in Ref. 1** it appears that aerofoils of this simple type are capable of giving high lift coefficients with very modest negative pressure coefficients.

The free streamline approach is of course only one possible method of obtaining an aerofoil section characterized by a more or less uniformly low pressure around the leading edge and over at least a large part of the upper surface, and the real problem arises in the necessity for achieving a solution (whether by variable geometry or not) that satisfies the requirements of both low speed and cruising flight.

5. Boundary-Layer Calculations

When this work was started, it appeared that a satisfactory calculation method for turbulent boundary layers with suction (or injection) might be achieved by the use of the entrainment equation, proposed earlier by one of the present authors[7] and the so-called "bilog law" of Black and Sarnecki.[8] The entrainment equation was based on the assumption that the rate of increase of mass flux in the boundary layer was controlled primarily by the velocity defect in the outer part of the layer, which could be related to the value of H, the conventional form parameter. Using two empirically determined curves, the development of H then could be calculated simply from the growth of momentum thickness and the increase of total mass flux in the boundary layer. The method had been found to work very satisfactorily for solid surfaces,[9] and it appeared equally applicable with suction or blowing.

The bilog law represented the velocity distribution in the wall region of the turbulent boundary layer with suction or injection in the same way as the normal log law represented

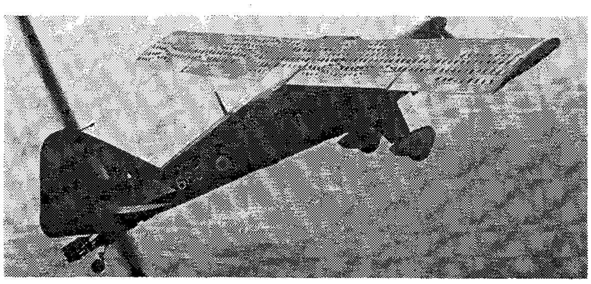


Fig. 16 Aircraft in steady level flight with suction.

** Ref. 1, pages 295–341.

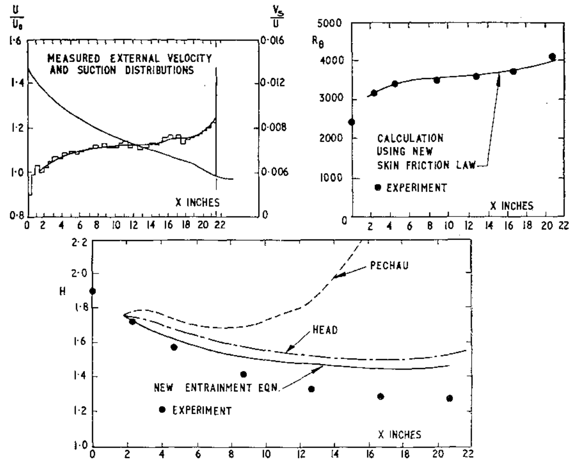
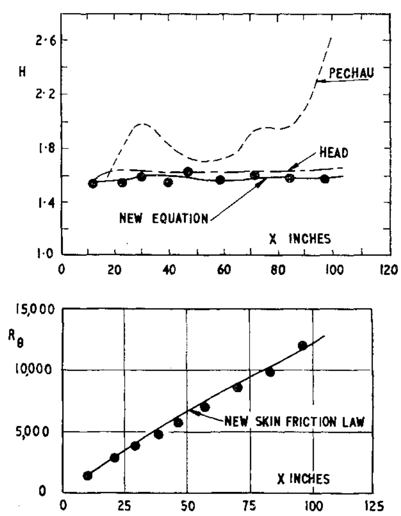


Fig. 17 Thompson's experimental and calculated results (case D).

it for solid surfaces; and just as the log law may be used with a suitable family of velocity profiles to determine a skin friction relationship of the form $c_f = c_f\ (R_\theta, H)$, so the bilog law can be used to determine $c_f = [R_\theta, H, (v_o/U)]$. Thompson has prepared skin-friction charts of this form and has recently presented[10] some comparisons between calculated and measured boundary-layer developments with suction and injection, using these charts and either the original entrainment equation or a somewhat improved version. Some of his results are presented in Figs. 17 and 18 which, incidentally, show the shortcomings of Pechau's method.

The calculation method used by Thompson has been programed by Krishnamurthy in order to carry out systematic calculations relevant to suction aerofoils generally, and to the present flight experiments in particular. Some of the results so far obtained are shown in Figs. 19 and 20 for the case where suction is applied to maintain a constant value of H in a pressure gradient similar to that measured on the upper surface of the aircraft wing at a moderately high lift coefficient. It shows the effect of maintaining different values of H and of different values of initial boundary-layer thickness. It will be seen that the suction quantities required generally are quite similar to those found necessary in flight, though the actual distributions of suction are of course very different, and suction could have been curtailed (at least for the low H values) quite far forward on the chord without bringing separation forward of the trailing edge. This indicates that present suction requirements probably could be substantially reduced. It will also be noted that the suction requirements do not increase particularly rapidly with increasing momentum thickness at the start of suction.

Fig. 18 Thompson's calculations for a layer with injection (V_0/U = 0.005) measured by Mickley and Davis (NACA TN 4017) run C-5-50.



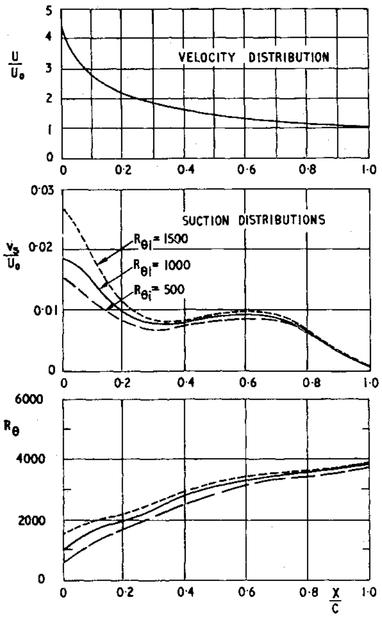


Fig. 19 Suction distributions to maintain $H = 1.4$ for different initial values of $R\theta$ chord Reynolds number $= 2 \times 10^6$.

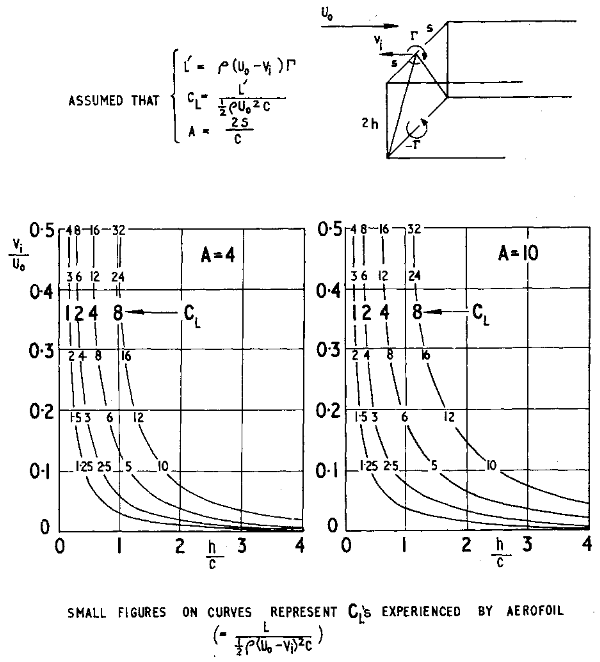


Fig. 21 Induced velocities at aerofoil assuming simple horseshoe vortex model.

6. Performance Calculations

Some time ago Edwards[11] used a computer to determine the effects of available lift coefficient on takeoff and landing distances for a wide range of aircraft parameters. It was found that the numerous curves that he obtained could be virtually collapsed by the use of suitable nondimensional parameters, and the results have been published[12] in this form. The basic nondimensional parameters involved in the problem are T/W, $C_{L\max}/A$, and $w/h\rho gA$ [or $w/h\rho C_{L\max}$], where h is the height of the obstacle to be cleared (customarily 50 ft) and the other symbols have their usual significance. It is found that the takeoff distance, expressed as a multiple of h, is primarily a function of T/W and $w/h\rho gA$ when $C_{L\max}/A$ is high (induced drag limited takeoff) and of T/W and $w/h\rho gC_{L\max}$ when $C_{L\max}/A$ is small (lift-limited takeoff).

As other investigations[13–15] have shown, considerable reductions in airfield length are made possible by the availability of high lift coefficients, particularly when the available thrust/weight ratios also are high. For example, at a T/W of 0.6, take-off distances to 50 ft are typically about halved by raising $C_{L\max}$ from 2 to 5, and further reductions in takeoff distance are apparently possible up to a $C_{L\max}$ of the order of 10, the usable C_L being taken as 0.9 $C_{L\max}$.

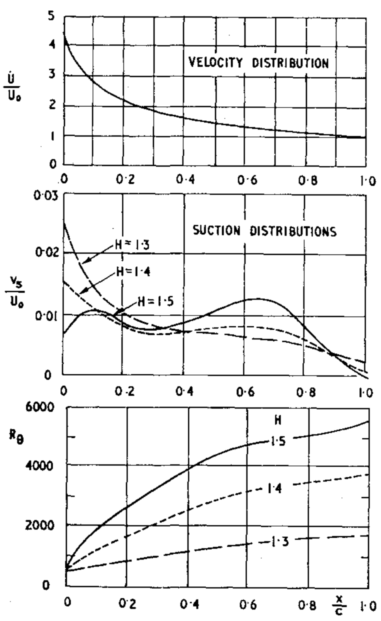


Fig. 20 Suction distributions to maintain different constant values of H $R\theta_i = 500$ chord Reynolds number $= 2 \times 10^6$.

The results of the calculations performed here and elsewhere appeared to confirm the usefulness of the present work, bearing in mind that suction might not bear the whole burden of increasing lift but might be used in conjunction with deflected slip-stream, conventional slotted flaps, or tilt-wings. In this last connection it may be worth remarking that difficulties that apparently have been encountered in the transition regime due to boundary-layer separations could presumably be eliminated by a direct application of the results reported here.

A factor that has been omitted in the takeoff and landing calculations mentioned, is what might be called the "wind-gradient effect".[16] A lifting wing close to the ground experiences an apparent reduction in airspeed due to the induced velocity generated by the image of the bound vortex representing the wing. There thus is a built-in tail wind that increases in magnitude as the incidence is increased for takeoff, and rapidly decreases as the aircraft climbs away. The effect will be to increase the ground run, but at the same time to give an increased initial rate of climb. In landing, too, the effect may be important in leading to a rapid decrease in apparent airspeed as the aircraft takes up the landing attitude, and stall-on at an increased still-air groundspeed. To obtain an idea of the order of magnitude of this effect, a simple horseshoe vortex model was assumed which leads to the results shown in Fig. 21. It will be seen that the effect becomes large for high lift coefficients and close proximity to the ground. This supports the use of the high-wing configuration for STOL aircraft and suggests that future landing and takeoff calculations might well take this effect into account.

7. Conclusions

This paper has attempted to outline progress in what set out to be a fairly comprehensive investigation of a topic that may or may not find practical application. It is hoped that the results achieved, along with those obtained elsewhere, will ultimately make it possible for the designer to make a realistic assessment in any given situation of the potentialities and limitations of this particular method of boundary-layer control.

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Use of Boundary-Layer Control on a Supersonic Attack-Reconnaissance Aircraft

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The application of lift augmentation through boundary-layer control (BLC) on a contemporary model high-performance carrier-based aircraft is discussed. Two distinct schemes for providing BLC are examined. Early models of the aircraft (A-5A) utilized BLC on the trailing edge flaps to obtain increased lift at low angles of attack. Later models (RA-5C) employ BLC on the leading edge in order to increase the maximum lift coefficient. Wind-tunnel test data are presented for both types of BLC. These data show the influence of various factors such as the amount of BLC and BLC distribution on the lift and pitching moment characteristics. The wind-tunnel results are compared with those obtained from flight tests of an instrumented aircraft. A comparison of the characteristics of the two types of BLC is also presented.

Introduction

THE increased emphasis on extended range and supersonic flight capabilities for carrier-based aircraft has confronted the aircraft designer with two conflicting aerodynamic requirements. The thin, highly swept, low aspect ratio configurations, necessary to fulfill the supersonic flight requirements, provide notoriously poor low-speed characteristics. The low-speed problems can be partially solved by increasing takeoff and landing speeds, thus requiring ever increasing runway lengths and emergency gear. However, when the added restriction of operating from the flight deck of an aircraft carrier is imposed, considerably more attention must be given to maintaining the reasonable takeoff and landing speeds inherent in low-speed aircraft.

The high degree of development of mechanical high-lift devices has enabled considerable reduction in takeoff and landing speeds of high-performance aircraft. Because of this refined development of mechanical high-lift devices, it was reasonable to assume that only relatively minor improvements in this area would be possible with the hardware available. This, coupled with the increased weight and complexity of these systems in order to keep the wing mold line of the retracted system intact so as not to compromise high-speed performance, has directed more attention to the application of BLC systems to improve low-speed characteristics.

The concept of preventing separation on a lifting surface with BLC was first demonstrated by Prandtl as early as 1904 through the use of a suction system. The application of BLC using tangential blowing at the leading edge of an airfoil was first proposed by Bauman in 1921. With the advent

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