FLIGHT TESTS AND WIND-TUNNEL MEASUREMENTS ON AEROFOILS WITH BOUNDARY LAYER SUCTION FOR INCREASING MAXIMUM LIFT

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ABSTRACT

It has been shown by flight tests with a German aeroplane of the type DO 27 that for a wing with suction at the nose nearly the same maximum lift coefficient can be obtained as for a wing with a slat. The total drag of the aeroplane with suction, however, is approximately 15 per cent smaller as compared with the aeroplane with slat.

SYMBOLS

GEOMETRICAL SYMBOLS

S	wing area, m^2
S_1	perforated area of the wing, m^2
b	wing span, m
d	hole diameter, mm
c	wing chord, m
α	angle of attack
γ	flight path angle with horizontal
ϑ	angle of wing chord with horizontal
η	deflection of trailing-edge flap
$A = b^2/S$	aspect ratio

AERODYNAMIC SYMBOLS

W	aircraft weight, kp
T	absolute temperature, °K
T_m	mean temperature, °K
C_L	lift coefficient
C_D	drag coefficient
C_M	moment coefficient
$C_Q = Q/VS$	coefficient of sucked volume flow
p_∞	ambient atmospheric pressure, kp/m^2
Δ_p	head of suction blower, kp/m^2
$q = (\rho/2)\, V^2$	dynamic pressure, kp/m^2
V	flight speed, m/s
V_s	Vertical component of velocity in gliding flight, m/s

OTHER SYMBOLS

P	horsepower of blower, hp
n	rotation speed of blower, min^{-1}
Δh	difference of flight altitude, m
τ, $\Delta\tau$	time, time difference, s

INTRODUCTION

The maximum lift of aeroplanes is limited by boundary layer separation precipitated by the severe adverse pressure gradients which occur on the highly curved regions of the upper surface at the wing nose and flap knee (see Fig. 1). By the application of boundary layer control the corresponding potential flow can sensibly be approximated. Boundary layer control may be applied by blowing out to reenergize the boundary layer or by suction to remove the retarded boundary layer. With the widespread adoption of the gas-turbine engine for aircraft propulsion large quantities of compressed air could be blown over the trailing edge. On the other hand, the stalling incidence can be substantially increased by nose blowing or nose suction, the latter being much more economical. The boundary-layer control at the wing nose and at the trailing-edge flap should be regarded as complementary rather than competitive. In the following we shall restrict ourselves to nose suction.

Early investigations on laminar profiles with nose suction through a slot have been undertaken by A. Walz [2] and the measurements, with varying position of the suction slot, show that with advancing suction slot maximum lift is increasing (Fig. 2).

The work of Walz was continued by Lighthill [3] who developed new nose shapes particularly designed for nose-slot suction. Although the experimental results [4] confirmed that the stalling incidence and maximum lift rose steadily with increasing suction quantity the suction requirements for such especially designed nose-slot aerofoils were unduly large even for shapes with larger nose curvature radius. As discussed theoretically by Thwaites [5] for an unseparated laminar boundary layer, area

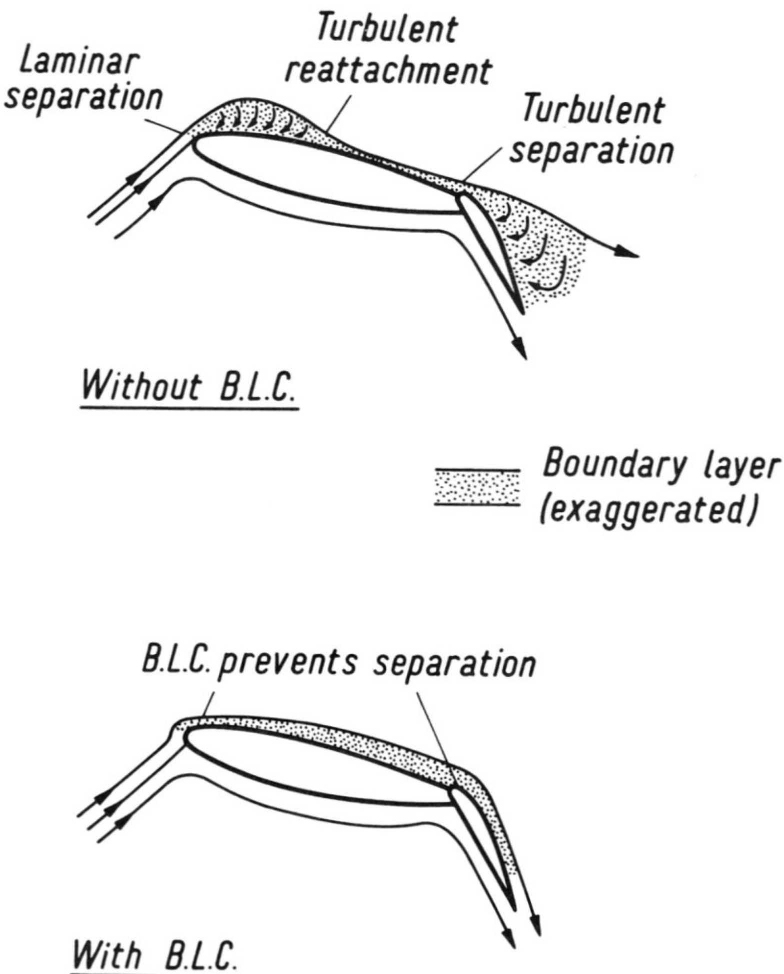


Figure 1. Flow without and with boundary layer control.

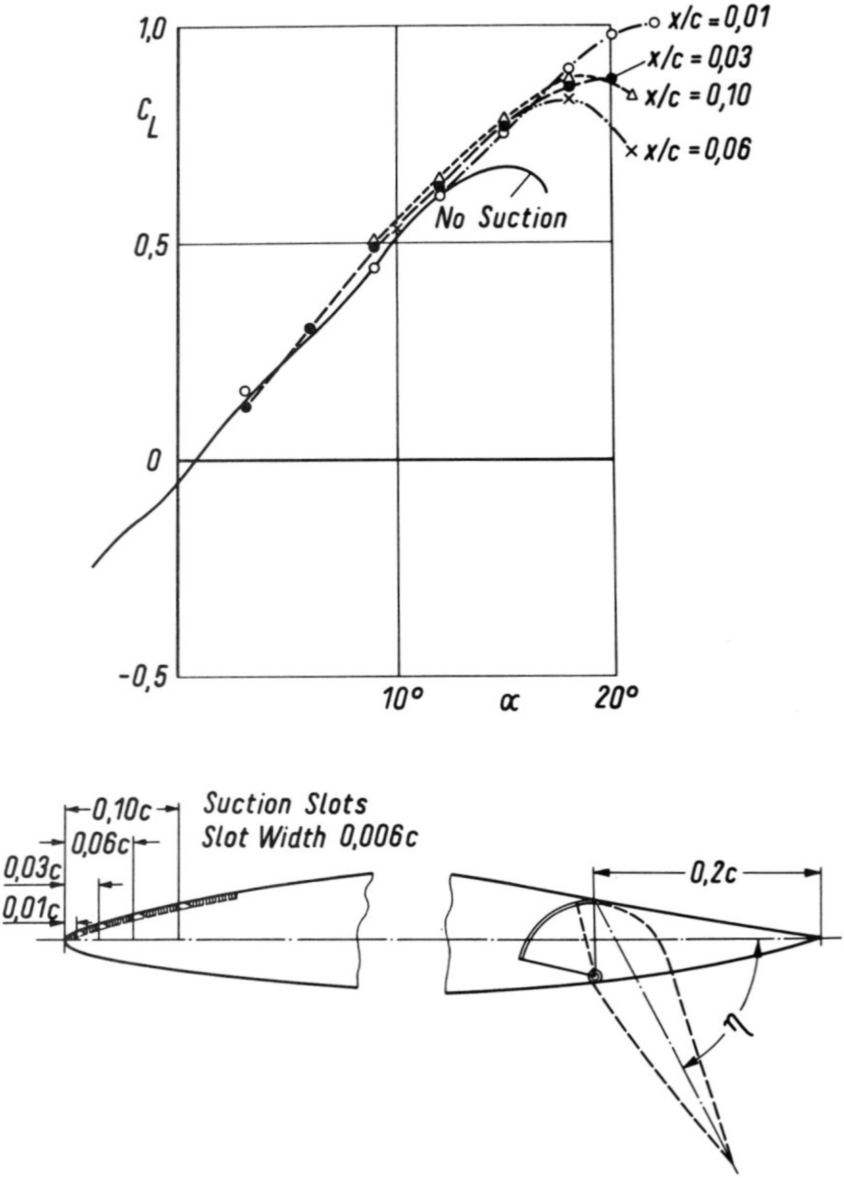


Figure 2. Lift characteristic of an aerofoil with one nose slot of different position, according to Walz [2].

suction on more conventional aerofoils seemed to be more economical than sink action by slot suction. At higher angles of incidence the boundary layer soon becomes turbulent, so that the theoretical results by Schlichting and Pechau [6] for turbulent boundary layers on aerofoils with nose suction give more realistic results for the necessary suction quantity. Several wind-tunnel measurements and flight tests on aerofoils with area suction in the nose region have been undertaken in England and America. Especially interesting are the measurements of Weiberg and Dannenberg [7] which show (Fig. 3) that with constant angle of incidence there always exists a

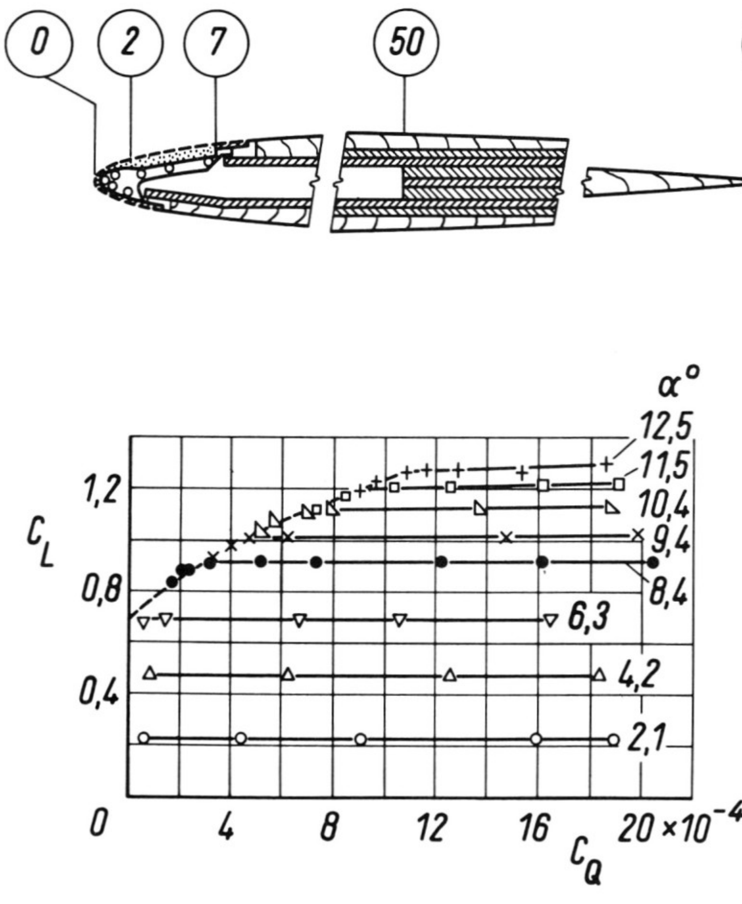


Figure 3. Lift characteristic of an aerofoil NACA 0006 with suction through a porous nose at constant incidence angle and increasing suction quantity [7].

minimum quantity of suction. Of course this is only true for prevention of nose separation. With a deflected flap the maximum lift increases with increasing suction quantity because the boundary layer on the flap knee becomes thinner. The application of a porous skin in the nose region leads to complicated structural problems. A much easier way is to approximate a porous nose by drilling rows of holes into the skin of the aerofoil. This method was perhaps first adopted by Atkins and Trayford [8]. It has also been used in the flight tests by Raspet, Cornish, and Bryant [9] and in the flight tests by Schwarz [10] with the German aeroplane RW-3a. In the RW-3a tests a strip between 4.1 and 21.5 per cent chord length on the upper side along nearly all the span excluding a narrow region in the neighbourhood of the fuselage, was perforated by rows of holes. With zero thrust (fixed propeller) and no trailing-edge flap deflection the maximum lift coefficient could be increased from $C_L = 1.11$ to $C_L = 1.97$ by a suction quantity $C_Q = 0.0022$. These results encouraged us to continue the measurements with a larger German aeroplane of type DO 27, where the limitations in space and weight for the installation of the suction device and the instrumentation were smaller than on the RW-3a.

The original aerofoil of the DO 27 is equipped with a slat giving a maximum lift coefficient of $C_L = 2.65$ with 45° flap deflection and without thrust. On the other hand, the slat causes relatively high resistance in cruising flight. For comparison both aerofoils, the original aerofoil with slat and the modified aerofoil with closed nose section and suction by rows of holes, were investigated by wind-tunnel measurements and flight tests.

WIND-TUNNEL MEASUREMENTS ON AEROFOIL SECTIONS

Pressure and wake distributions have been measured for the profile Gö 818 with nose suction and on Gö 819 with slat (Fig. 4) in the low-turbulence wind-tunnel of the AVA Göttingen [11]. Only some of the results with trailing-edge flap deflection 0° and 60° are selected in Fig. 5 which are of special interest for comparison with the flight tests. Of course the unperforated profile reaches only low maximum lift coefficient, but with a suction coefficient of $C_Q = 0.0022$ a large lift increase is obtained. With flap deflection the maximum lift is higher with suction than with the slat; the opposite is true for no flap deflection. An interesting feature is the low drag of the suction aerofoil in the cruising speed range (Fig. 6). When suction is applied, the drag is further diminished and is approximately one third of the drag of the aerofoil with slat. For 12 different cases the development of the boundary layer has been measured with very fine probes. Figure 7 shows that without suction the boundary layer separates

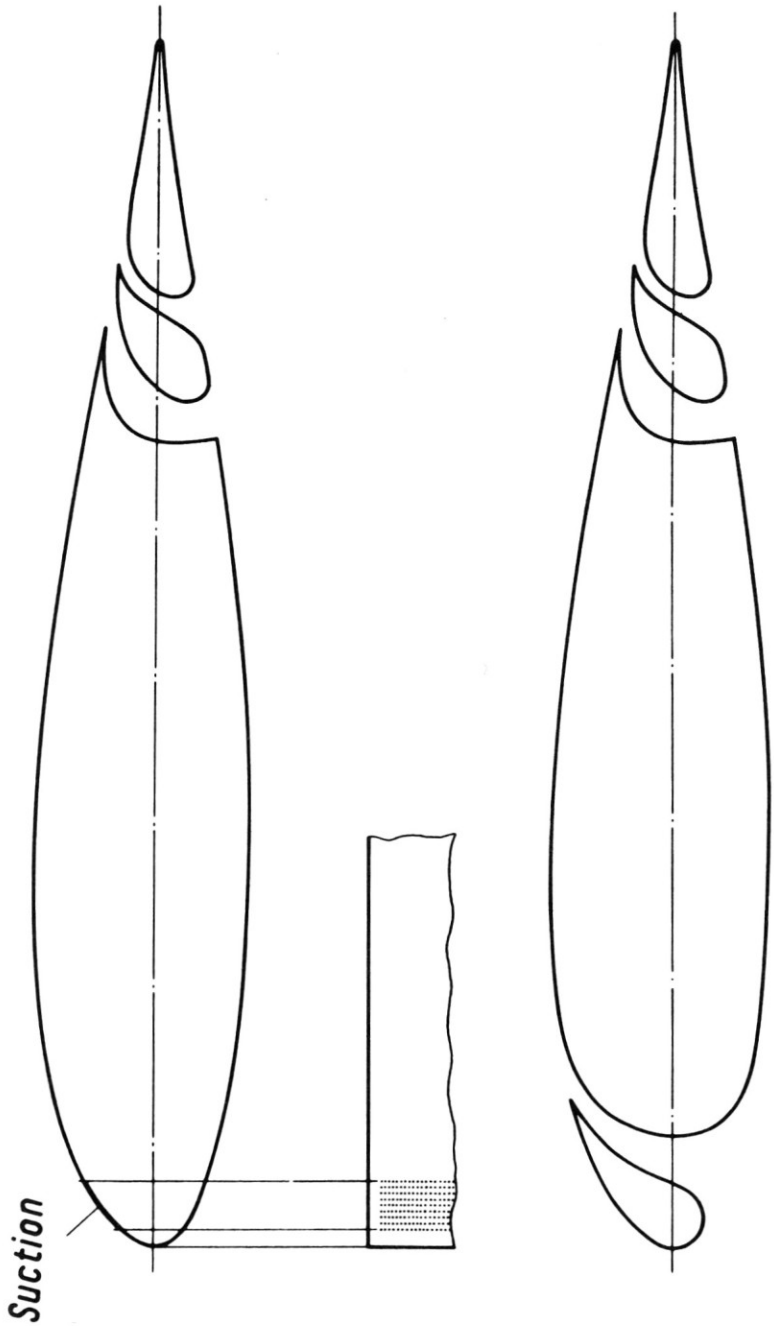


Figure 4. Aerofoils Gö 818 (with nose suction) and Gö 819 (with slat) [12].

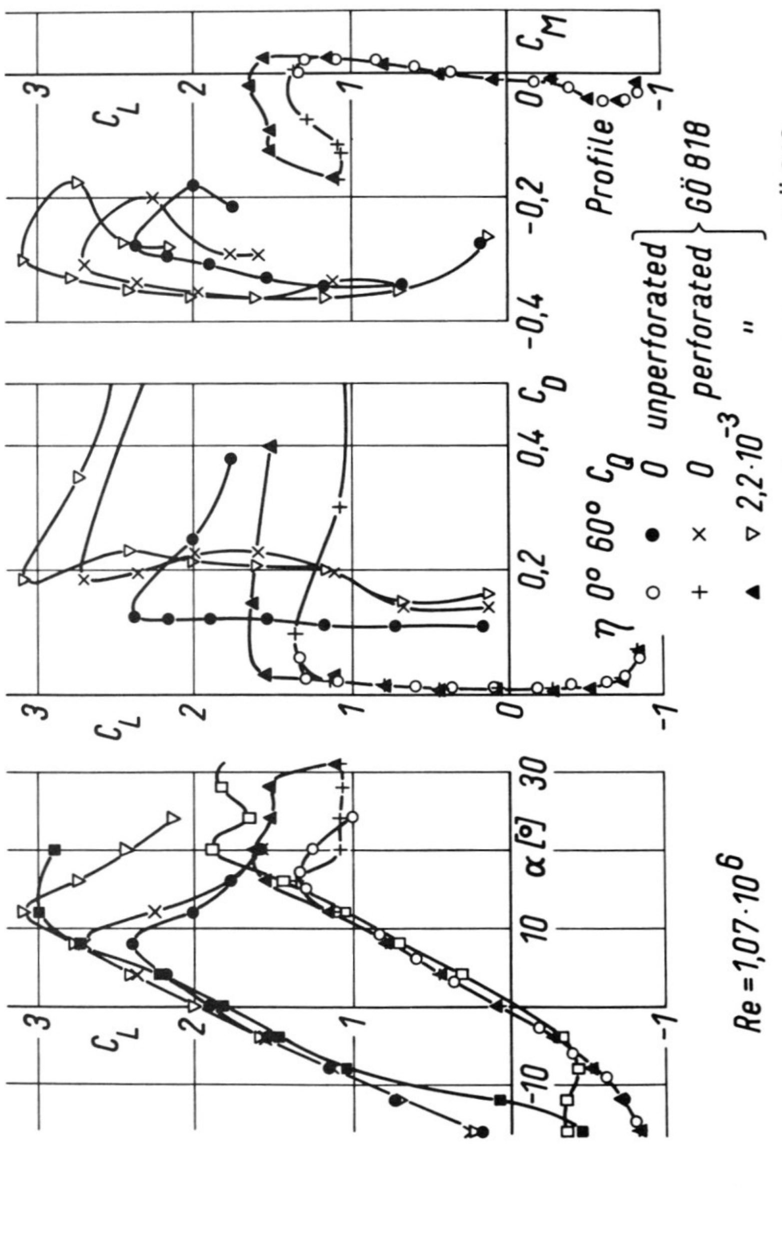


Figure 5. Wind-tunnel measurement on the aerofoils of Fig. 4 without flap deflection and with 60° flap deflection at different nose conditions. Re = $V\,c/\nu$ = 1.1×10^6 [11].

for an angle of attack $\alpha = 16°$, whereas with suction there is no flow separation. It is interesting that the curves for $\alpha = 8°$ and no suction are nearly parallel to the corresponding curves for $\alpha = 16°$ with suction. All curves with suction begin with an extended laminar part.

FLIGHT TESTS

In nonaccelerated flight the flow direction at some point of the aeroplane depends only on the incidence angle α. The angle α can therefore be

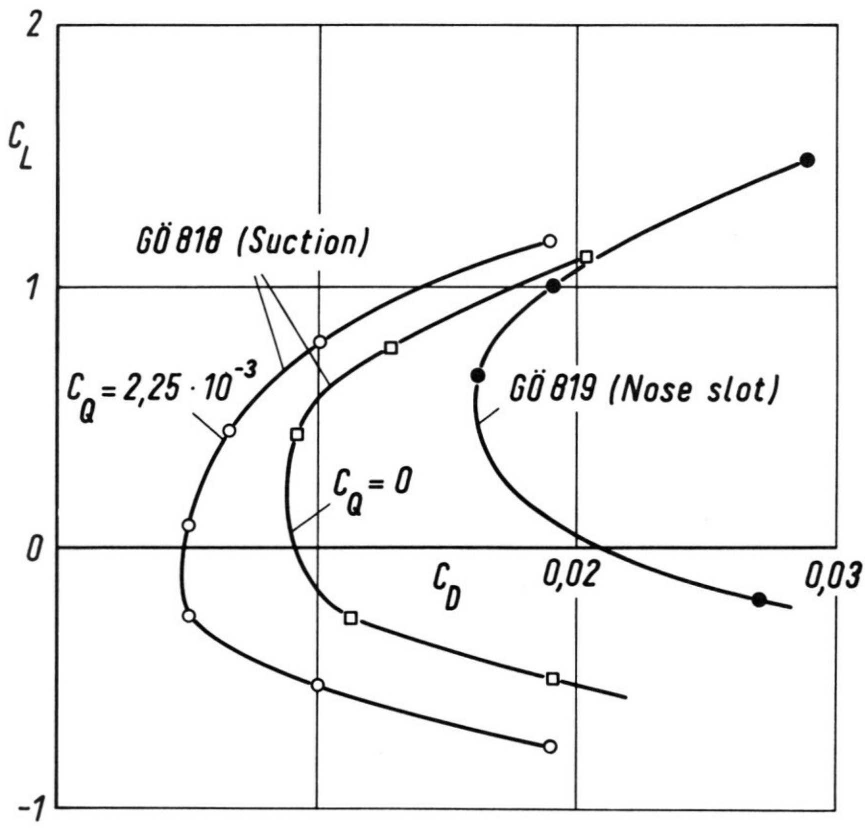


Figure 6. Comparison of the polar diagram of the aerofoils of Fig. 4 (without flap deflection). Re = 1.1×10^6 (Ref. 11).

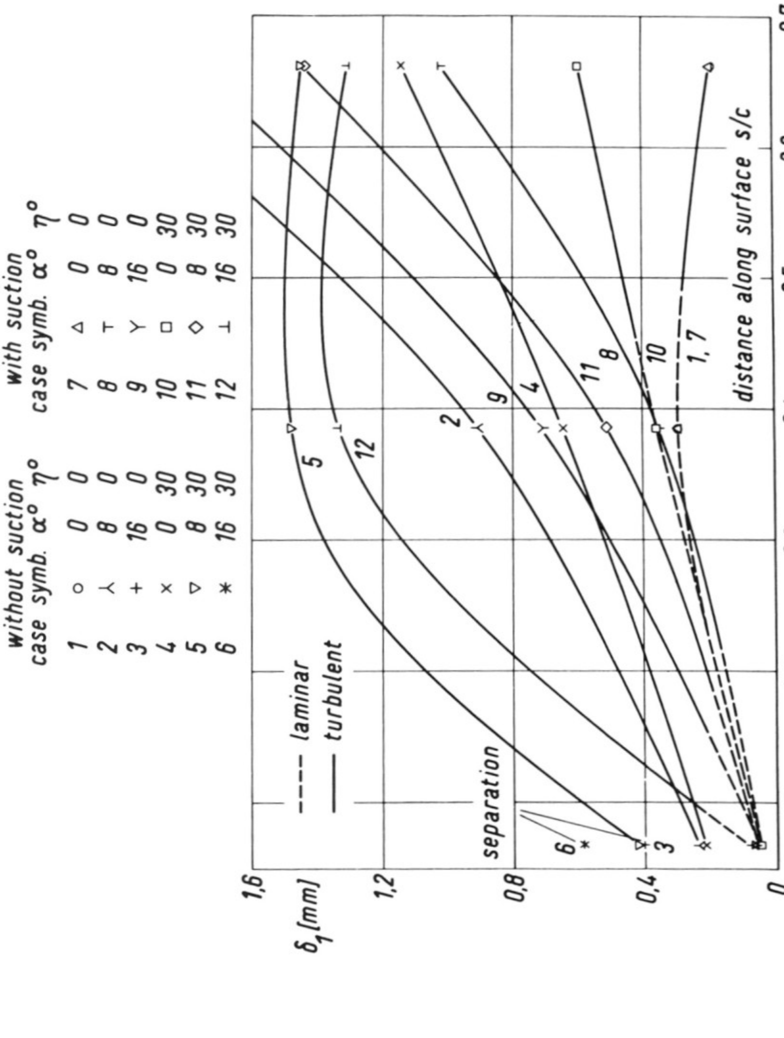


Figure 7. Wind-tunnel measurements on the development of boundary layers on the suction aerofoil Gö 818 (Ref. 13).

determined by the measurement of the flow direction. When the angle of pitch ϑ also is known, the gliding angle γ is determined by Fig. 8.

$$\gamma = \alpha - \vartheta$$

and the lift and drag coefficients are given by

$$C_L = \frac{W \cos \gamma}{qS}$$

$$C_D = \frac{W \sin \gamma}{qS}$$

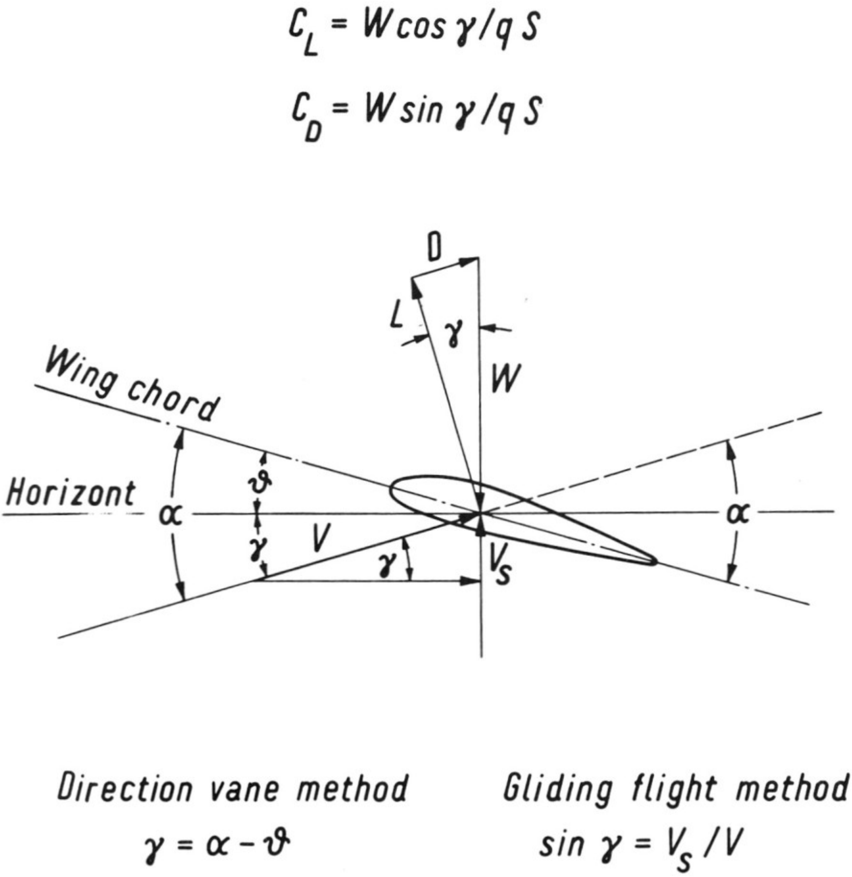


Figure 8. Explanation of different flight-test methods.

On the other hand, according to Fig. 8 there is also

$$\sin \gamma = V_s/V$$

where V_s is the vertical velocity component. The vertical velocity, however, can be evaluated from the pressure-time-diagram of a barograph according to the formula:

$$V_s = \frac{\Delta h}{\Delta \tau} = \frac{h_2 - h_1}{\Delta \tau} = \frac{1}{\Delta \tau}[18.4 + 0.067(T_m - 273.2]\ 10^3 \frac{p_1}{p_2} \qquad \text{m/s}$$

where $\Delta \tau$ is the time difference in seconds between two pressure readings and T_m is the mean temperature (°K). Obviously two flight-test methods are possible, the first called "direction-vane method," the latter "gliding flight method." With the direction-vane method the three values α, ϑ, q must be measured or recorded during flight; with the gliding flight method the five values ϑ, q, τ, p_∞, and T must be recorded. As in the latter case a sufficient height difference is necessary for determining the vertical velocity; the time needed for this test method is about five times as large as for the direction-vane method. The gliding flight method is therefore expecially used as a reference method. On the other hand, the direction-vane method suffers from difficult calibration, which also may be influenced by landing-flap deflection.

In the present flight tests, both methods have been used and Fig. 9 gives a general view of the aeroplane and shows the location of instrumentation. The pitot-static pressure has been calibrated by towing a specially designed static probe; the pitch angle was recorded by a very sensitive recording pendulum level. Two different flow direction vanes with remote control have been especially designed for these measurements. For eliminating the propeller thrust the measured difference of undisturbed total pressure and the total pressure in the propeller slip stream was correlated to the thrust. All instruments were combined in a multichannel recorder which was fixed on an oscillation-free desk of special design. A detailed description of instrumentation is given by Schwarz and Wuest [12].

The original nose section of the DO 27 aeroplane was removed and replaced by a suction nose with rows of holes (Fig. 10). The diameter of the holes was 0.5 mm, the spanwise distance between them was 2.5 mm, and the chordwise spacing varied from 3.5 to 12 mm, as is shown in Fig. 10. The total number of holes was 151,000 and the ratio of the perforated area to the total aerofoil area 0.00153. In order to save time, the holes were drilled with a rapid drilling machine making 1–2 holes per second with a maximum solidity of approximately 5,000 holes for one drill.

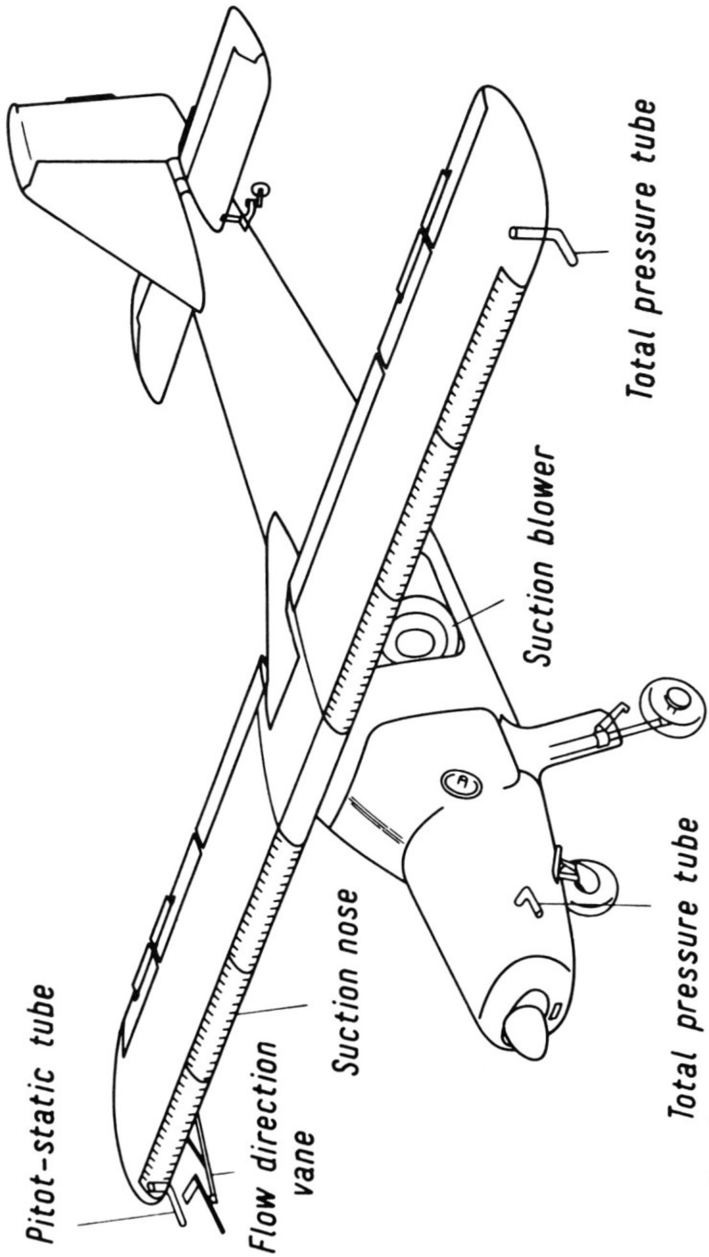
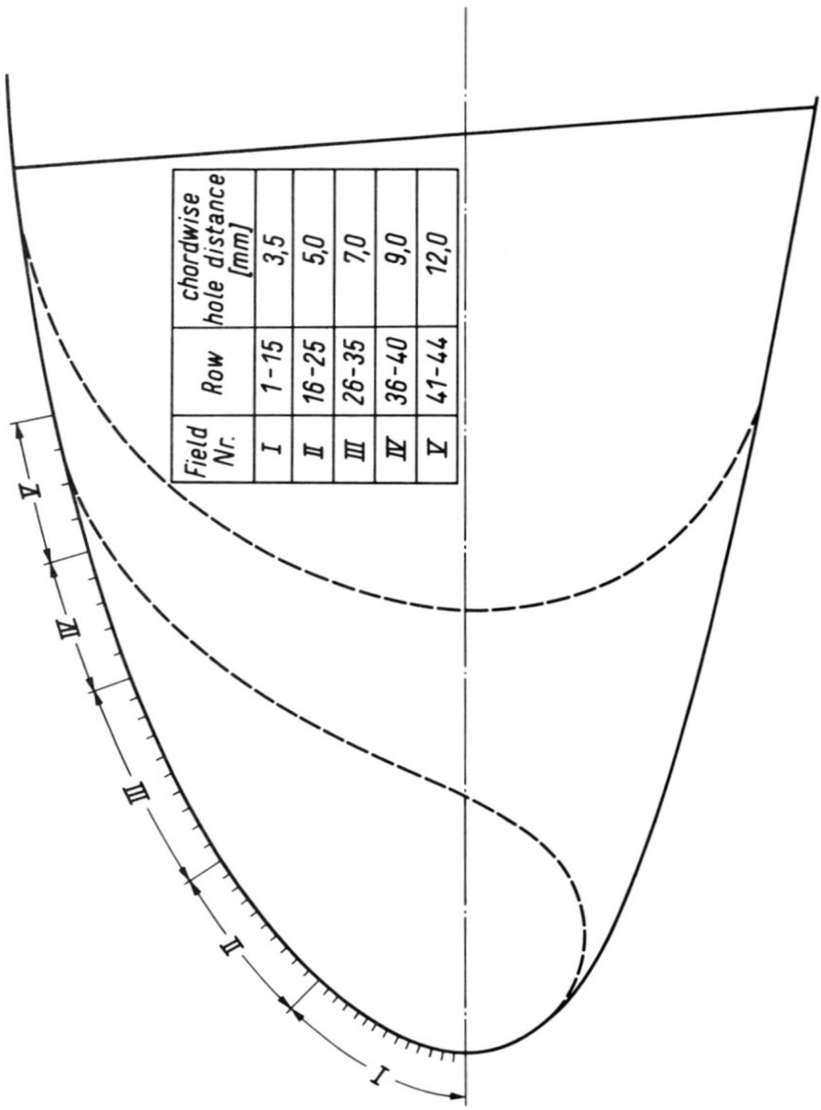


Figure 9. German aeroplane DO 27 with special arrangement and instrumentation for flight test with suction.



Field Nr.	Row	chordwise hole distance [mm]
I	1-15	3,5
II	16-25	5,0
III	26-35	7,0
IV	36-40	9,0
V	41-44	12,0

Figure 10. Nose of the suction aeroplane with position of the holes (dotted lines indicate aerofoil with slat).

The axial blower which has been used for the flight tests, has been specially designed. The spiral housing is made from plastics to save weight. The rotor, however, must be made from steel because the rotation speed reached 7,000 revolutions per minute. The characteristic of the blower has been determined by a ground test using orifice meters with 27-m tube length for measuring the flow quantity.

By a special device the suction quantity could be adjusted to be a given fraction of the cruising speed multiplied with aerofoil area, i.e., C_Q could be held constant for varying speed.

ANALYSIS OF TEST RESULTS

The flight tests by F. Schwarz began in March 1962 on the airfield of Kassel with the original DO 27 (with slat). A great deal of testing was necessary for the calibration of the instrumentation. After modification of the aeroplane further tests with suction were conducted from Oberpfaffenhofen near Munich. The tests were violently broken off by a fatal accident in October 1962, when they were nearly finished.

Before the proper measurement of flight polars the stalling behaviour especially of the modified aeroplane, was thoroughly investigated at altitudes between 2,000 and 3,500 m (6,700 and 11,500 ft). The stalling tests were repeated after installation of the suction blower and modification of the suction ducts. The stalling speed was dependent on suction, trailing-edge flap deflection and propeller thrust. The following values were measured:

TABLE 1. STALLING SPEED [Kn] OF THE DO 27 WITH SUCTION AEROFOIL

η	No thrust			Full thrust		
Flap	C_Q of suction			C_Q of suction		
	0	0.0015	0.0020	0	0.0015	0.0020
0	56	49	—	49	40	—
35–45°	42	39	—	36	31	25

When the suction was suddenly interrupted the aeroplane pitched down by the nose, but returned to normal flight after a loss of altitude of approximately 50 m. During the stalling tests with suction the aeroplane reacted only upon very hard movement of the controls and pitched down to the left, returning to normal flight after 20 m loss of altitude. The suction holes have never got dirty during the flight tests and also in rainy weather no influence on the efficiency of suction could be detected. It is also interesting that with very high incidence angles and separated flow on the fuselage the aeroplane was fully manoeuvrable with suction on.

By analysis of the flight tests polars have been evaluated and plotted in Fig. 11 for different suction quantities and different flap deflections. For comparison also a flight test with the original aeroplane with slat and zero flap deflection is added. With zero flap deflection the maximum lift coefficient is $C_L = 1.95$ with slat and 1.85 for the suction aerofoil with $C_Q = 0.002$. With deflected flap the maximum lift coefficient was higher for the suction aerofoil than for the aerofoil with slat according to the previous wind-tunnel measurements. Unfortunately, polars have only been measured in flight for the deflected flap with the suction aerofoil. But a comparison with other flight test data of the original DO 27 aeroplane shows that the suction aerofoil has at least equivalently high lift to the original aerofoil, when the trailing-edge flap is deflected. The drag coefficient at cruising speed is 15 per cent less for the aeroplane with the suction aerofoil. In the wind-tunnel measurements the reduction of the profile drag was from $C_D = 0.016$ for the aerofoil with slat to $C_D = 0.005$ for the suction aerofoil. The absolute drag reduction measured in the flight tests was of the same order, but as the total drag of the DO 27 aeroplane (with nonretractable landing gear) is very high ($C_D = 0.06$), the relative drag reduction is less evident.

Figure 12 shows the lift coefficients for the different cases as a function of the incidence angle. The agreement between the wind-tunnel measurements and the flight tests is very good, if the finite aspect ratio is considered in the analysis of the flight tests.

The power requirement for the suction is given by the product of suction quantity and pressure difference between the aerofoil surface at the holes and the blower exit. If the minimum pressure in the hole region is $C_p q$ the pressure difference must be at least $(C_p + 1)q$ (if the exit is in a region of stagnation pressure) and the required power is

$$\Delta P = (C_p + 1) C_Q \, SqV$$

The peak value of the pressure minimum in the nose region may be of the order $C_p = 12$ so that for an assumed velocity of 20 m/s one has with $S = 19.4 \text{ m}^2$ and $C_Q = 0.002$:

$$\Delta P = 13 \times 0.002 \times 19.4 \times 24 \times 20 = 242 \text{ kp} \quad \text{m/s} = 3.2 \text{ hp}$$

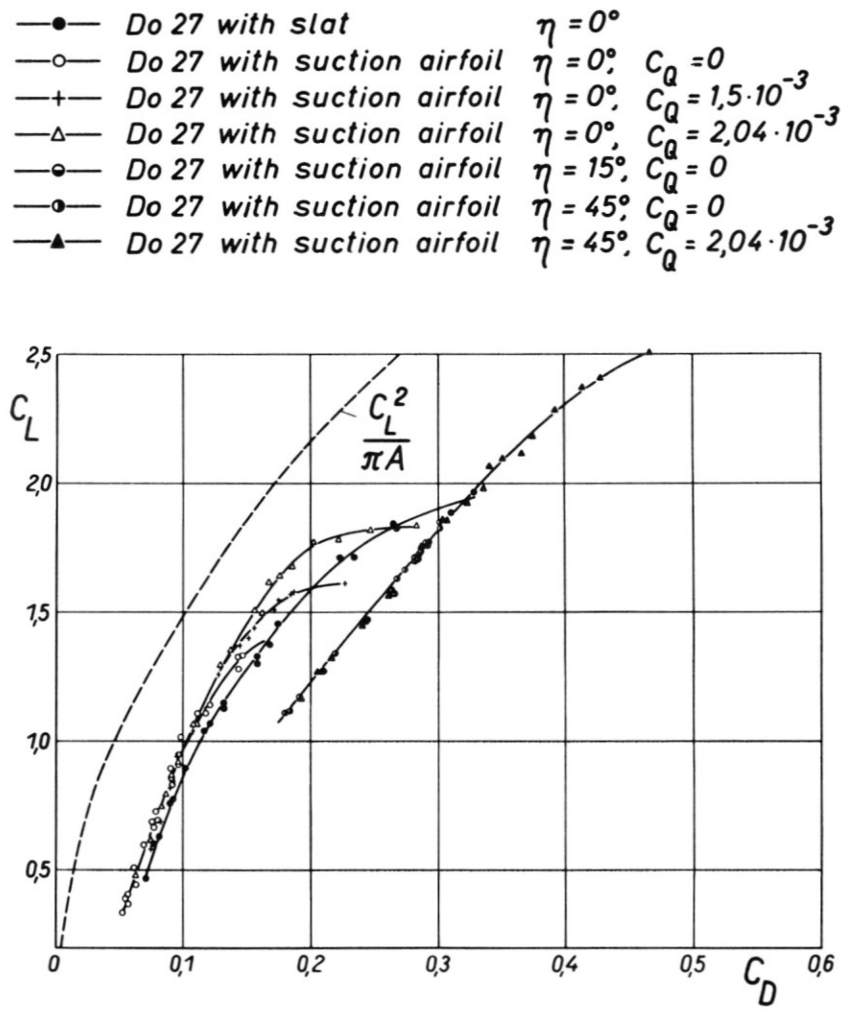


Figure 11. Polar diagram of the German aeroplane DO 27 with suction in comparison to the original aeroplane with slat.

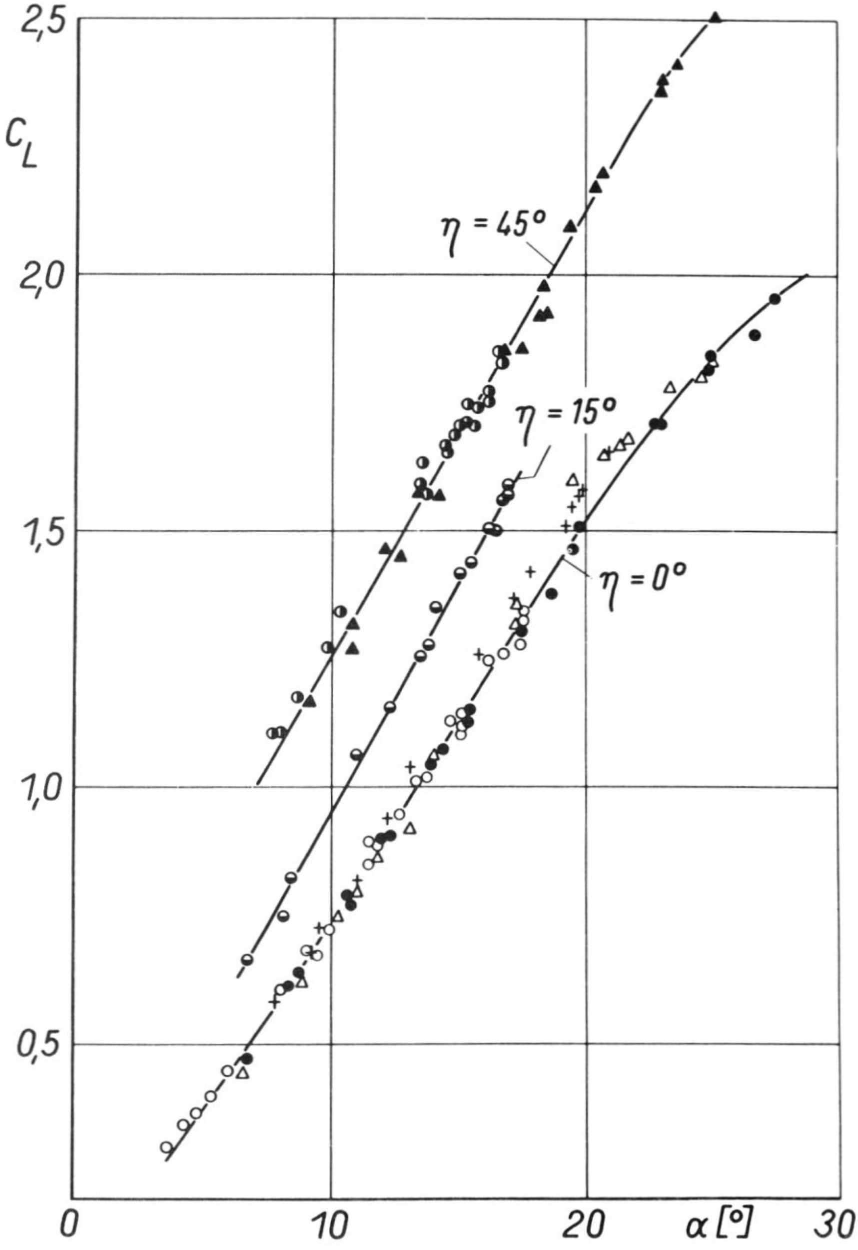


Figure 12. Lift coefficients of the German aeroplane DO 27 with suction in comparison to the original aeroplane with slat.

In fact, there must be a pressure drop through the perforated skin of at least the same order, so that a power

$$\Delta P \approx 8 \text{ hp}$$

is required for the suction aerofoil without considering additional losses in the ducts from the blower to the aerofoil. In the present aeroplane, the additional losses were very high because of unfavourable conditions for the subsequent installation of the blower. Better solutions would be possible for a specially designed suction aeroplane.

In cruising flight the velocity is higher, but $C_p \sim 1.4$ is small and therefore the power requirement for suction to reduce the drag is of the same order. With a total power of 275 hp and a total drag coefficient in cruising flight of $C_D = 0.06$ the suction power would correspond to an additional drag

$$\Delta C_D = 0.06 \times \frac{8}{275} = 0.00175$$

and therefore a net drag reduction remains.

CONCLUSIONS

The boundary-layer control by suction in the nose region is an effective means for increasing maximum lift. The values of maximum lift are very similar to those obtainable with a slat. The use of rows of holes is a very convenient and satisfactory possibility of applying boundary-layer suction. It has been shown that by sucking, in cruising flight the net drag can be reduced, also considering the power requirement for suction. The stalling behaviour of such an aeroplane is quite regular and no trouble due to dust or rain was observed.

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COMMENTARY

H. VOGEL (*British Aircraft Corporation (Operating) Ltd., Luton Division, Luton Airport, Luton, Beds., England*): Could the speaker give some indication of the differences in longitudinal trim or pitching moment characteristics for the aircraft with continuous (i.e., uninterupted) leading-edge suction relative to the aircraft with the basic wing fitted with leading-edge slats?

REPLY

From the wind-tunnel measurements it follows that the moment coefficients are nearly equal for the wing with leading-edge suction and for the basic wing with leading-edge slat.

COMMENTARY

G. L. LAMERS (*Technological University of Delft, Holland*): With regard to the wind-tunnel measurements you have discussed I should like to ask if there are any hysteresis effects at the stall of the aerofoil with suction. In other words, when the angle of attack of the aerofoil with suction is increased, the aerofoil will stall, say at about 20°. When the angle of attack is decreased from above the stall, is unstalled flow then regained at 20°, or at a much lower angle of attack?

REPLY

A systematic investigation of possible hysteresis effects, when decreasing the angle of attack from stall, was not undertaken, but some preliminary tests showed no evidence of such effects.

COMMENTARY

Y. MANNÉE (*N.L.R., Sloterweg, Amsterdam*): In the polar diagrams of Fig. 5 of the printed paper it appears that at equal lift coefficients the drag coefficients with flaps down ($\eta = 60°$) is much higher for the suction case than for the unperforated profile. As the C_D for the suction case has not been corrected for the suction power, what is the explanation for this difference? (For the flaps-up case the C_D with suction is lower than without suction, Fig. 6, as can be expected.)

REPLY

Because it is more interesting to have low drag in cruising flight, no attempt was made to get also low drag at high lift. No explanation could be found for the higher drag with deflected flap and suction compared with the unperforated wing.

COMMENTARY

D. G. CLARK (*Cambridge University, Engineering Laboratory, Cambridge, England*): The speaker has understandably restricted the major part of his discussion to the comparison of the effectiveness of the slat and fairly concentrated nose suction, but the wider potentialities of distributed suction should not be overlooked. In this connection the experiments of Cornish, mentioned by the speaker, were impressive in demonstrating that with suction distributed over the full chord of the wing and flap, a $C_{L_{max}}$ in excess of 5 could be obtained with very modest suction power.

Flight experiments currently in progress at Cambridge with rather more suction power available than in the experiments reported by the speaker confirm his general conclusions regarding the effectiveness of nose suction, and this work is now continuing with suction applied further aft through discrete strips of perforations. The stalling lift coefficient of the aircraft, flaps undeflected, and with power on to retain attached flow over the centre section, has been raised from 1.6 to approximately 5 by this means, although it was necessary to modify the wing leading edge to reduce the leading-edge suction peak to a level within the capabilities of the suction unit before this value was possible. Chordwise pressure distributions corresponding to section lift coefficients of 3.0–3.5 have been measured.

We also find that behaviour after sudden loss of suction is docile, with immediate nose down pitch, and the pilot can avoid a stall entirely by easing the control column forward as soon as the effect is felt.

Regarding a previous query about hysteresis at the stall; sufficient nose suction appears to impart thick aerofoil stalling characteristics to the section, and we have found no evidence of hysteresis. Even from angles of attack as high as 40°, the stall is docile and recovery is rapid with a loss of height of only about 50 ft.

REPLY

In wind-tunnel measurements with another aerofoil (German airplane RW-3a) we made additional investigations on the influence of suction through strips of holes in the aft part of the upper surface of the wing. No influence was found without flap deflection, but with deflected flap the high lift was increased. To be sure, the leading-edge suction peak was relatively high and better results may be expected with other aerofoils having larger nose curvature radius.

COMMENTARY

D. K. M. MENDELA (*Hawker Siddeley Aviation, DeHavilland Division, Hatfield, Herts., England*): Could Dr. Wuest comment on the effect of suction on aircraft stability at the stall and in the approach to land configurations with particular reference to speed stability during the approach to land? How was the lateral control and longitudinal control affected during the speed reduction down to the stall?

How strong was the ground effect?

What was the aircraft attitude during the approach and at the touch-down point?

REPLY

All flight tests were made in sufficient altitudes for security reasons. No investigations of ground effects have been undertaken. The wind-tunnel measurements, too, did not include ground effects.