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Wind-tunnel Tests on the NPL 434 Nose-slot Suction Aerofoil

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Summary.—Stalling tests were made on the 8 per cent thick section NPL 434†, which has been specially designed for nose-slot suction. At the higher suction quantities, the maximum lift of the aerofoil was considerably greater than for the Lighthill and Glauert sections previously tested when due allowance was made for the difference in camber. At low suction quantities, there was no improvement.

Tests with various slot widths showed that the velocity into the slot as well as the suction quantity was important in relation to high maximum lift, and that the values of $C_{L\max}$ achieved with suction were determined more nearly uniquely by the momentum coefficient rather than by the quantity coefficient. Static pressure measurements made in the slot and ducting indicated that the suction head required at the stall was high, being at least equal to the dynamic head in the slot throat, but that some reduction could be expected from improvements in the slot entry shape.

1. *Introduction*.—Previous low-speed wind-tunnel tests on the thin nose-slot suction aerofoils NPL 403[2] and NPL 404[3], designed by Lighthill[4] and Glauert respectively, have been compared in Part I of R. & M. 2693[1]. In the design of these sections, the severe adverse velocity gradients over the nose at high incidences were concentrated in an abrupt velocity fall, with only small adverse gradients to the rear. Suction was applied through a slot at this abrupt fall to prevent boundary-layer separation there. The experiments showed that the stalling incidence and maximum lift rose steadily as the suction quantity was increased, but that the suction quantities required to achieve useful gains were unduly large.

Subsequent theoretical investigations (Part II of R. & M. 2693[1]) on sections of this type indicated that much better results would be obtained if the position of the abrupt velocity fall were located further back than in the Lighthill and Glauert sections and if the nose radius were simultaneously increased. Low-speed stalling tests of NPL 434†, which has its slot at $0 \cdot 02c$ from the leading edge and a ϱ_L of $0 \cdot 02c$, have now been carried out in the National Physical Laboratory 4 ft (No. 1) Wind Tunnel to determine whether the improvements expected theoretically can be realized in practice.

The symbols used in this report are defined in the Appendix.

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† NPL 434 was previously designated D2/4 by Williams[1]. The ordinates of the section are listed in Table 1 of the present report, and the shape is drawn out in Fig. 1.

2. *Experimental Set-up.*—The metal nose of the aerofoil (Fig. 1) was constructed so that the slot width could be varied by sliding the front lower portion (A) along a line (DE) parallel to the tangent to the aerofoil contour at the slot position. Tests were carried out at slot widths of 0·02 in., 0·03 in. and 0·05 in. The rear of the aerofoil was made of wood, and the aerofoil spanned the working-section (4 ft square) of the tunnel; the aerofoil chord was 18 in.

Internal ducting of the Rawcliffe type[5] was used. It was divided at mid-span and connected to external pipe-work symmetrically arranged on either side of the tunnel (*see* Fig. 2), the suction being provided by a centrifugal blower housed outside the tunnel room.

All the tests were done at a wind speed of 40 ft/sec, giving a Reynolds number of $0 \cdot 38 \times 10^6$.

3. *Reduction of Observations.*—The lift force was obtained from the measured pressure distributions. No corrections have been applied for tunnel interference (except where explicitly stated), as the main interest is in results at the stall where the usual theoretical correction for tunnel constraint (lift effect)* is invalid.

Static-pressure measurements were made in the slot walls at the throat and just upstream of the partitioning teeth (where the air is turned into the collector duct), and also at the collector exit and in the calibration pipe leading to the suction control valves. To obtain qualitative estimates of losses in the slot and duct, the mean total heads given by adding the static pressure to the dynamic head corresponding to the local mean velocity were compared.

4. *Results.—Lift Curves.*—Figs. 3 to 5 show the lift *vs.* incidence curves for a range of suction quantities and slot widths. The maximum lift coefficients are plotted in Fig. 6 against the suction quantity coefficient C_Q.

Without suction, the lift curves were identical for all slot widths. The $C_{L\max}$ was 0·78 as compared with 1·12 for the Lighthill and Glauert sections, the reduction being partly due to the smaller camber of the new section.

With suction, the $C_{L\max}$ increased to 1·22 at a C_Q of 0·0052 for the 0·03-in. slot†, which becomes much the same as was obtained for the Lighthill and Glauert sections if due allowance is made for the difference in camber. At a C_Q of 0·0099, however, the $C_{L\max}$ rose to 1·76, which is about 0·3 greater than the value realized for the two previous sections. This improvement is not as much as was hoped for when the section was designed, but even so it becomes about 0·5 when allowance is made for the difference in camber.

The narrowest slot ($w = 0 \cdot 02$ in.) gave the highest $C_{L\max}$ for a given C_Q-value, but the slot losses were then the highest (*see* later)‡. This increase in $C_{L\max}$ as slot width is reduced shows that for nose-slot suction the slot velocity is important as well as suction quantity in determining the maximum lift. A comparison of Fig. 6 showing $C_{L\max}$ plotted against C_Q with Fig. 7 showing $C_{L\max}$ plotted against the momentum coefficient C_μ $[= 2C_Q^2 c/w]$ demonstrates clearly that C_μ is the more satisfactory parameter.

The value of $\partial C_L/\partial \alpha$ at low incidences without suction was about 5·7 per radian when reduced by a factor of 6 per cent to allow for wind-tunnel constraint (lift effect), the same as for the Lighthill and Glauert sections. This value is about 14 per cent lower than the theoretical

* This would reduce the measured lift-curve slopes at low incidences by about 6 per cent.

† Higher values of $C_{L\max}$ for $C_Q = 0 \cdot 0052$ were achieved in some subsequent tests. They have not been included in this report, however, because the reason for the improvement could not be ascertained.

‡ Tests at the larger C_Q-values were not carried out for the narrowest slot, as they would not be attainable in full-scale conditions owing to choking of the slot.

value of 6·6. As the suction quantity was increased $\partial C_L/\partial \alpha$ tended to increase, the highest (corrected) value obtained being about 6·3, and simultaneously the angle of zero-lift decreased.

Velocity Distributions and Flow Characteristics.—The experimental velocity distributions (with suction) are compared with the theoretical values in Figs. 9 and 10. Although the agreement is good at low incidences, it is poor near the nose at high incidences. In the theoretical design, the nose shape was chosen to provide (with suction) a rising velocity from the stagnation point at the nose up to the slot and a steadily falling velocity to the rear of the slot; boundary-layer separation was therefore expected to begin near the trailing edge. However, from the low velocities recorded experimentally in the vicinity of the slot, it appears that a localized region of separated flow appeared there as the incidence was increased. Wool-tuft observations confirmed this and showed that the stall developed as a rearward movement of the position of reattachment. Simple boundary-layer calculations indicate that the C_Q-values employed would barely suffice to remove the laminar boundary layer at the slot position for the higher incidences, because of the low Reynolds numbers of the tests. It is therefore expected that at full-scale flight Reynolds numbers the theoretical design characteristics of the section should be realized more closely than in the wind-tunnel tests.

Hysteresis.—Results obtained with C_Q decreasing, as compared with C_Q increasing, seldom differed. Hysteresis was observed only for suction quantities close to those just needed to suppress the bubble of separation at the nose, and even so was very limited.

Slot and Duct Losses.—Fig. 8 gives values of the ratio $(H_0 - H_p)/q_t$, the loss in mean total head between the free stream and the calibration pipe divided by the mean dynamic head in the slot throat. This was found to increase markedly with increasing slot width or decreasing C_Q, and was appreciably higher for suction at maximum lift than for suction at zero wind-tunnel speed. Since the loss $(H_t - H_p)$ in mean total head between the slot throat and the calibration pipe was only about $0 \cdot 1 q_t$ (except with the widest slot), it appears that the entry losses were unnecessarily high due to the simple slot entry shape employed.

The suction-head coefficient $C_H[(H_0 - H_p)/q_0]$ required to provide a given $C_{L\max}$ decreased as the slot was widened (*see* Fig. 6), but C_Q increased and there was little change in the power coefficient $C_Q C_H$. In practice, the minimum slot width will probably be decided by choking considerations or by suction-head limitations.

5. *Conclusions.*—The maximum lift of the NPL 434 aerofoil increased steadily as the suction quantity was increased (see Fig. 6). The $C_{L\max}$ was raised from 0·78 without suction to 1·76 with $C_Q = 0 \cdot 01$, $C_H = 33$ and slot width $0 \cdot 0017c$; the large value of C_H was due partly to the poor slot entry. The least value of C_Q needed to realize a given $C_{L\max}$ occurred for the narrowest slot, but C_H was then greatest and there was little change in the power coefficient $C_Q C_H$. It was found that the values of $C_{L\max}$ obtained for the various slot widths were determined more nearly uniquely by C_μ rather than by C_Q (*see* Fig. 7).

With the larger suction quantities ($C_Q \simeq 0 \cdot 01$), the $C_{L\max}$ was about 0·5 higher than for the earlier Lighthill and Glauert sections when due allowance was made for the difference in camber. With the smaller suction quantities ($C_Q \simeq 0 \cdot 003$) there was no improvement, but it is thought that at flight Reynolds numbers the improvements expected from theoretical design considerations should be more closely achieved than in the wind-tunnel tests.

Since the NPL 434 section was intended for use on high-speed aircraft, the effect of the unusual nose shape on the high-speed performance of such a wing section needs to be investigated experimentally. Low-speed stalling tests on swept-back wings incorporating the section are also desirable, to find if the tip stall can be suppressed economically by suction through the nose slot.

LIST OF SYMBOLS

c	Wing chord
C_Q	Suction quantity coefficient $= M/\rho_0 U_0 S'$
C_H	Suction head coefficient $= (H_0 - H_p)/\frac{1}{2}\rho_0 U_0^2$
C_μ	Suction momentum coefficient $= Mv_t/\frac{1}{2}\rho_0 U_0^2 S' = 2C_Q^2 c/w$
H_0	Free-stream total head
H_p	Mean total head in calibration pipe
H_t	Mean total head in slot throat
M	Mass rate of flow through slot
q_0	Dynamic head in free stream
q_t	Mean dynamic head in slot throat
S'	Wing area corresponding to spanwise extent of boundary-layer control
U	Velocity over aerofoil
U_0	Free-stream velocity
V_t	Mean velocity in slot throat
w	Suction slot width
x	Chordwise distance behind leading edge (per unit chord)
y	Ordinate perpendicular to chord-line (per unit chord)
α	Angle of incidence of chord-line to free stream
ρ_0	Air density in free stream
ϱ_L	Nose radius

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No.	*Author*	*Title, etc.*
1	J. Williams	Some investigations on thin nose-suction aerofoils. R. & M. 2639. April, 1950. Part I: A comparison of the stalling properties of some thin nose-suction aerofoils. Part II: A theoretical investigation on thin high-lift aerofoils specially designed for nose-slot suction.
2	F. Cheers, W. G. Raymer and Ola Douglas	Tests on a Lighthill nose-suction aerofoil in the N.P.L. 4-ft No. 2 Wind Tunnel. R. & M. 2355. April, 1947.
3	F. Cheers and Ola Douglas	Tests on a Glauert nose-suction aerofoil in the N.P.L. 4-ft No. 2 Wind Tunnel. R. & M. 2356. April, 1947.
4	M. J. Lighthill	A theoretical discussion of wings with leading-edge suction. R. & M. 2162. May, 1945.
5	A. G. Rawcliffe	Suction-slot ducting design. R. & M. 2580. April, 1947.

TABLE 1

Ordinates of NPL 434 *Nose-slot Suction Aerofoil*

x/c	y_u/c	y_l/c	
0	0	0	$\varrho_L/c = 0 \cdot 02$
0·003	0·01130	0·00990	
0·005	0·01460	0·01220	
0·01	0·02020	0·01548	
0·0125	0·02203	0·01645	
0·016	0·02352	0·01744	
0·02	0·02248	0·01833	← Slot on upper surface
0·025	0·02046	0·01958	
0·03	0·02026	0·02082	
0·04	0·02081	0·02309	
0·05	0·02175	0·02511	
0·075	0·02437	0·02931	
0·1	0·02686	0·03268	
0·15	0·03106	0·03779	
0·2	0·03429	0·04137	
0·25	0·03659	0·04374	
0·3	0·03798	0·04502	
0·35	0·03829	0·04510	← Maximum thickness $0 \cdot 083c$
0·4	0·03719	0·04369	
0·45	0·03515	0·04127	
0·5	0·03245	0·03815	
0·55	0·02928	0·03451	Wedge tail
↕	Straight line	Straight line	
1·0	0·0005	0·0005	

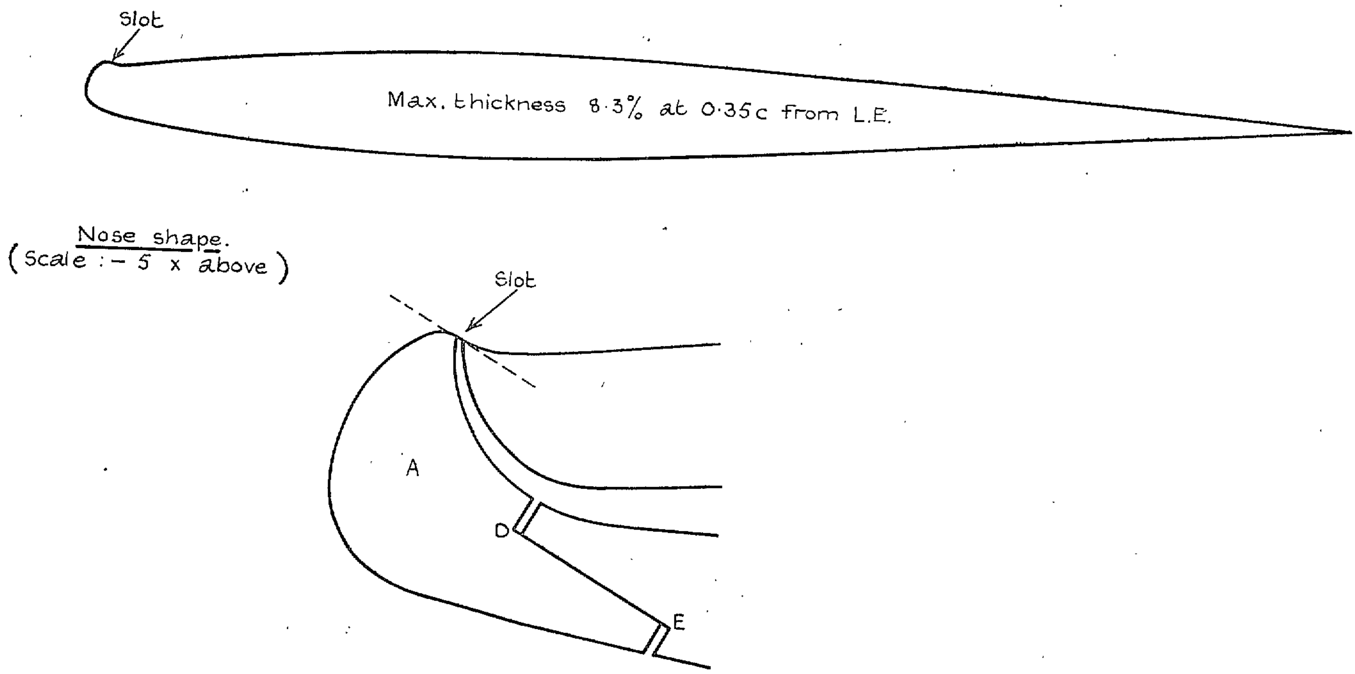

FIG. 1. Shape of NPL 434 nose-slot suction aerofoil.

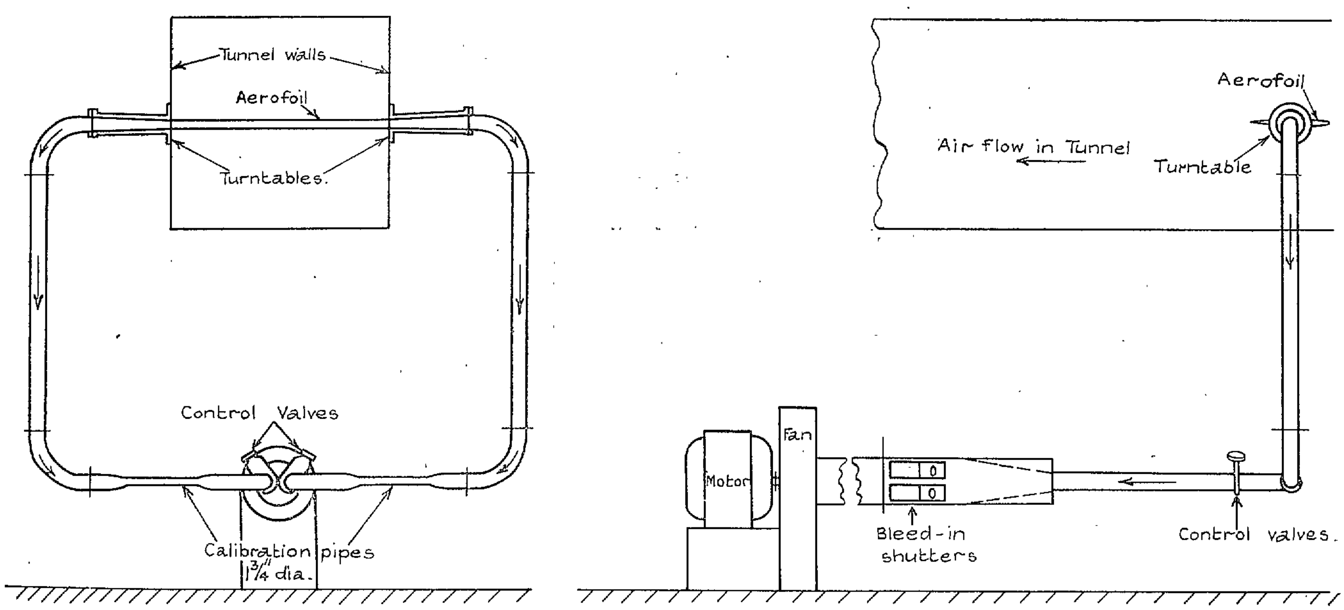

FIG. 2. Arrangement of ducting and pump.

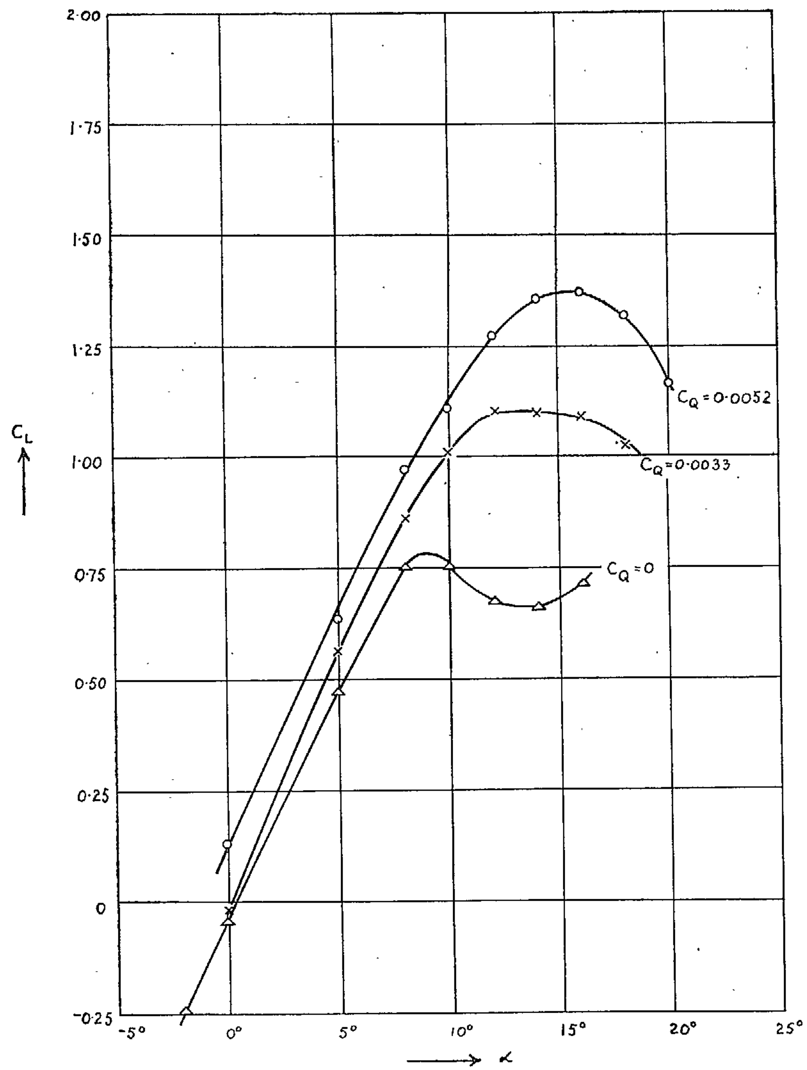

FIG. 3. Lift *vs.* incidence curves for NPL 434 with slot width 0·02 in.

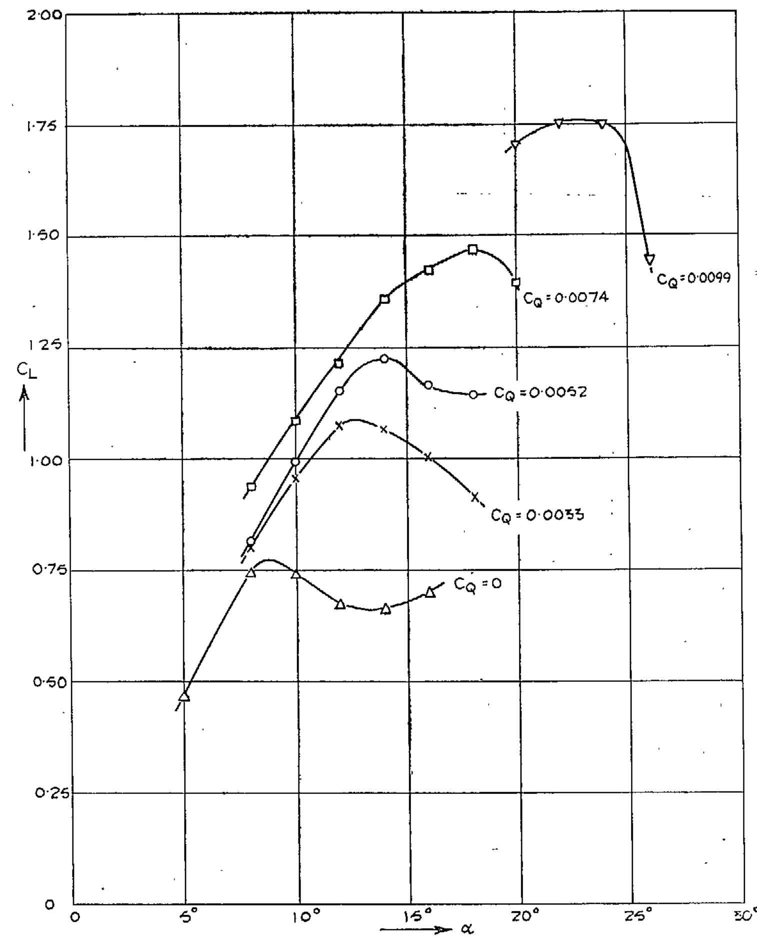

FIG. 4. Lift *vs.* incidence curves for NPL 434 with slot width 0·03 in.

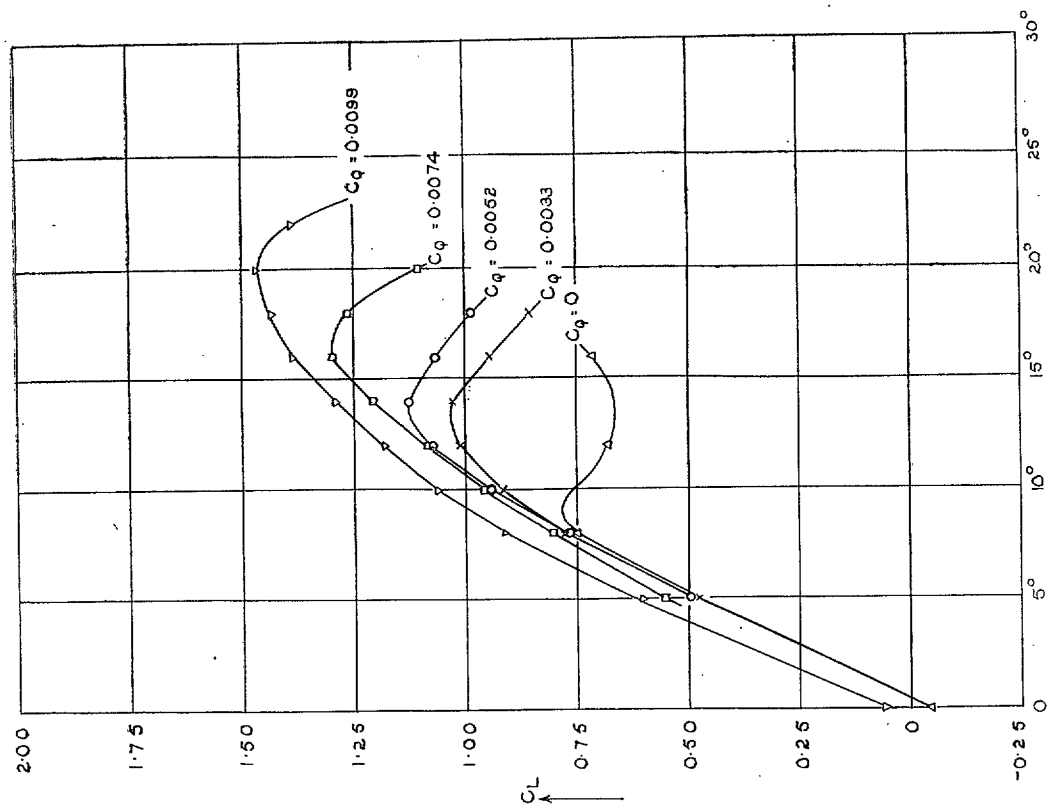

FIG. 5. Lift *vs.* incidence curves for NPL 434 with slot width 0·05 in.

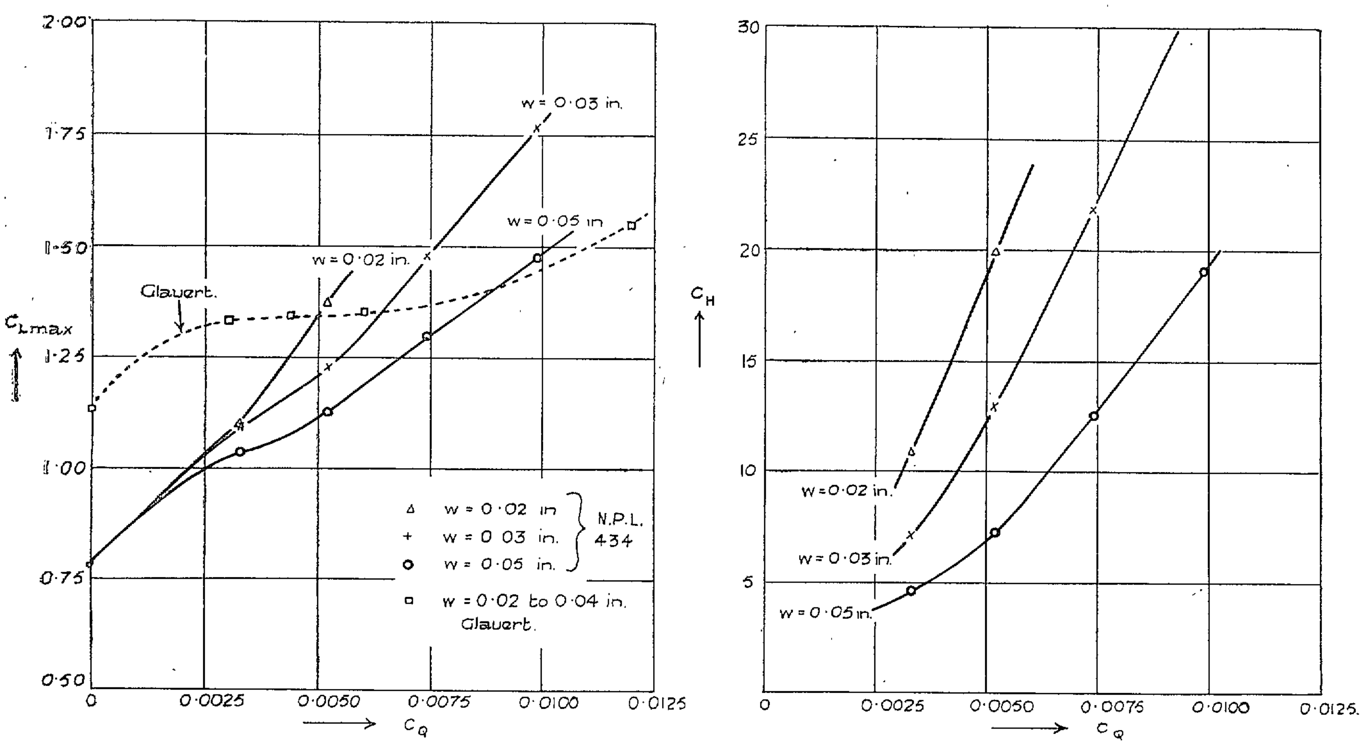

FIG. 6. Variation of maximum lift and of suction head with suction quantity.

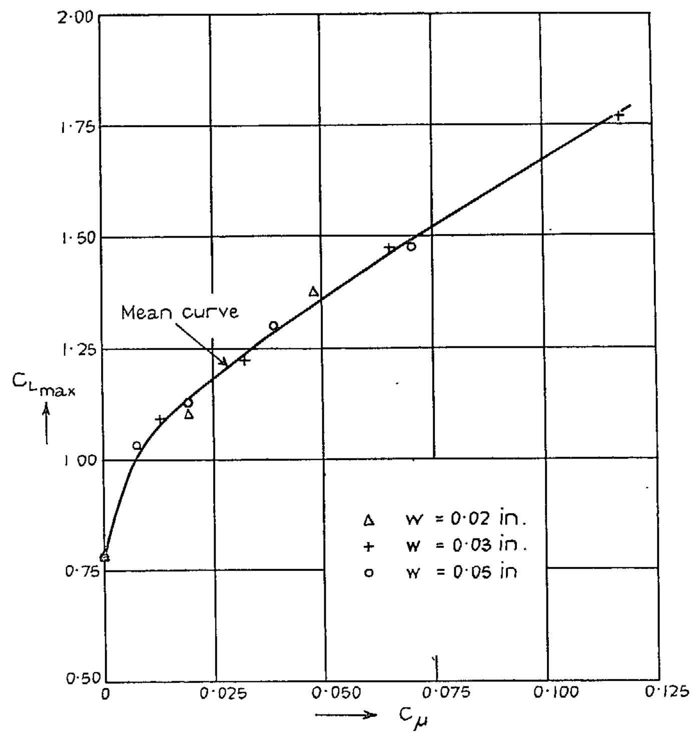

FIG. 7. Variation of maximum lift with suction momentum coefficient.

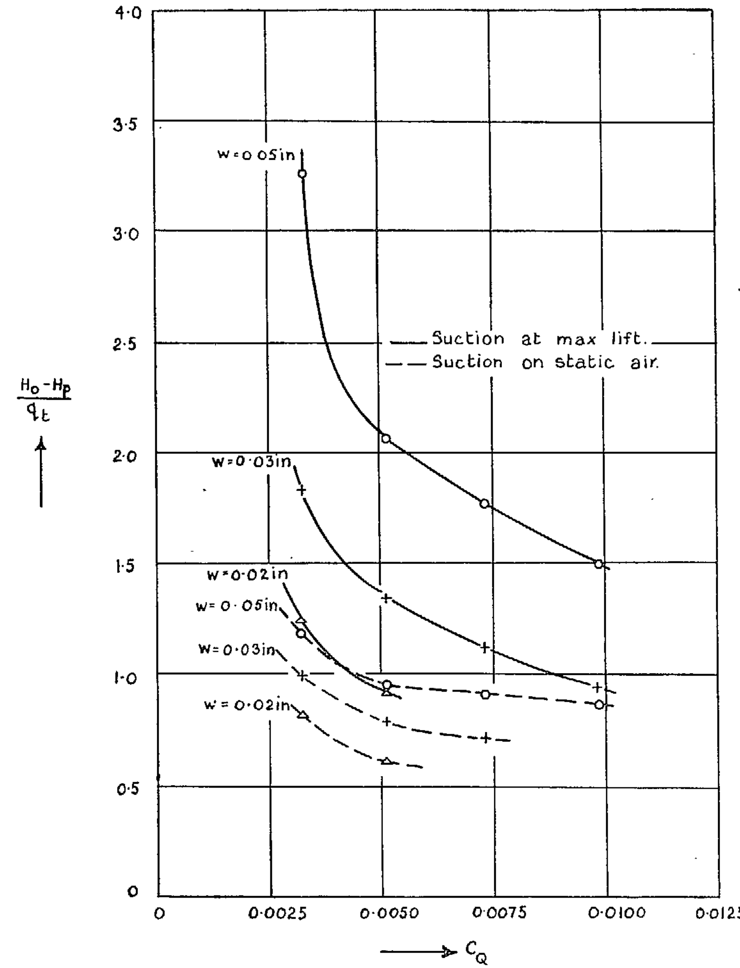

FIG. 8. Ratio of suction head required to dynamic head in slot throat.

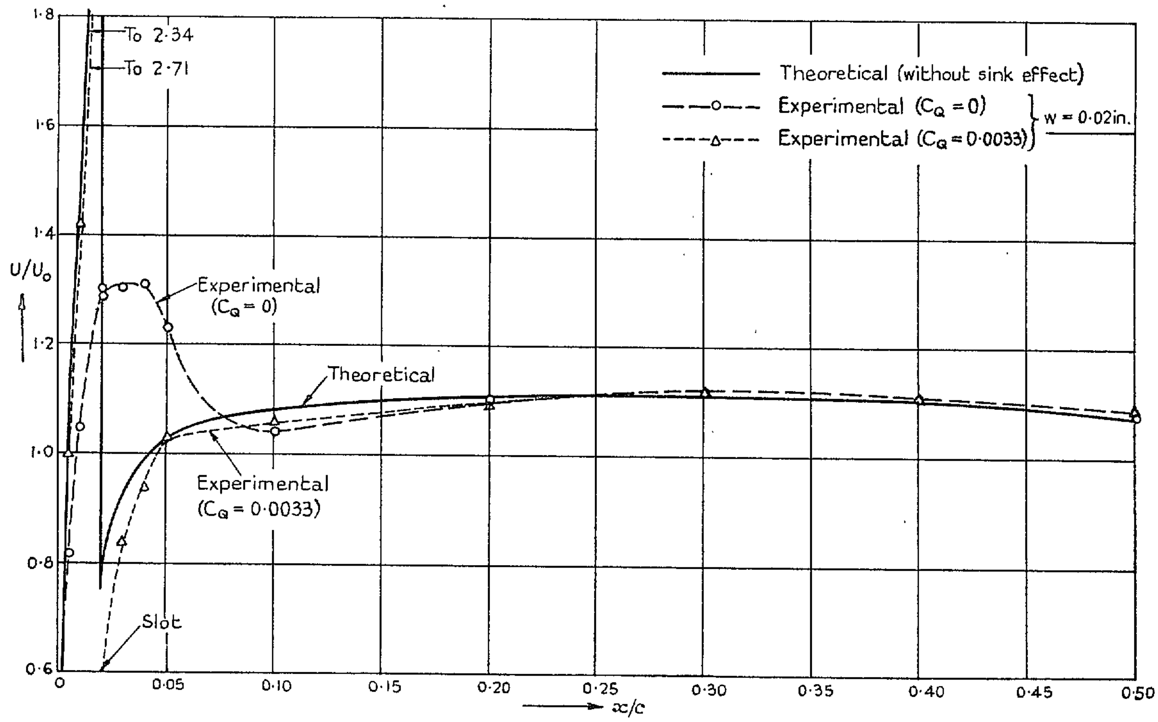

FIG. 9. Comparison of theoretical and experimental velocity distributions on upper surface of NPL 434 at zero incidence.

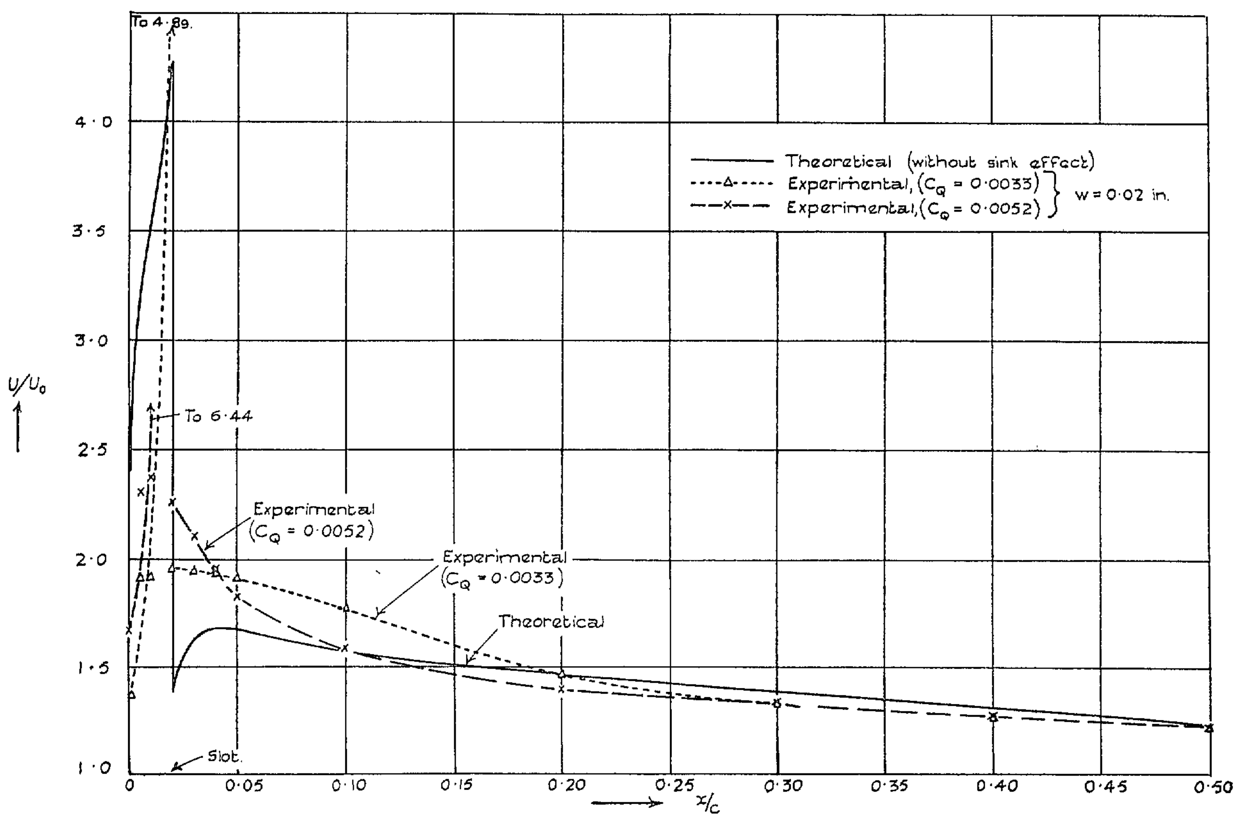

FIG. 10. Comparison of theoretical and experimental velocity distributions on upper surface of NPL 434 at 10 deg incidence.

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