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The Design of Suction Aerofoils with a Very Large C_L-Range

By

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of the Aerodynamics Division, N.P.L.

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Introduction.—The use of suction slots to remove the boundary layer at points where the air velocity has a discontinuity opens up wide new fields in aerofoil design. It becomes possible to envisage aerofoils which have laminar flow characteristics over the greater part of the surface throughout a C_L-range so large as to completely cover the normal flight range, and which are also thick enough to provide ample room for the stowage of engines, passengers and other loads at much lower all-up weights than have hitherto been feasible.

This paper considers four aerofoils designed on the basis of their velocity distributions in two-dimensional incompressible potential flow. The design method used was that of Lighthill's exact theory, set out in R. & M. 2112[1], which involves prescribing the velocity over the aerofoil surface as a function of position on the circle into which the aerofoil may be transformed. A few additional techniques to procure suitable velocity distributions were employed, and an exposition of these will be the subject of a later paper.

The principal feature in the design is the replacement of the region of falling velocity over the rear part of the aerofoil by a single discontinuity in velocity, at which point boundary-layer suction is applied. Thus adverse pressure gradients are completely eliminated throughout a wide range of incidence. The boundary layer remains thin and laminar flow may be achieved, even on aerofoils of very great thickness. At the discontinuity the mathematical shape is a logarithmic spiral, but this must be modified in practice to include the suction slot. In one aerofoil the spiral is avoided by having a steep fall of velocity over a short distance of the surface instead of a complete discontinuity, but this may detract from the performance.

The paper discusses the relative merits of the aerofoils and considers possible improvements. Zero pitching moment is very desirable and can readily be achieved. A suction slot on the lower surface proves to be unnecessary for aerofoils cambered as these are so as to be efficient at high lifts, but it may be unavoidable if a less cambered design is required in an effort to get a higher critical Mach number. This is inevitably low with aerofoils of this thickness, and is the chief drawback of thick suction wings.

Description of Aerofoils.—Each of the first three aerofoils is designed to have a C_L-range extending over 15 deg. and to have its main suction slot at about $0 \cdot 7$ chord from the leading edge. This gives in each case a C_L-range from $C_L = 0$ to $C_L = 2 \cdot 0$ and a thickness of about 30 per cent.

The aerofoil GLAS I is required to have a single slot with as small a discontinuity as reasonably possible, and consequently it is arranged that the velocity shall fall gradually from the slot to the trailing edge. There are no significant differences between the velocities on the upper and lower surfaces near the trailing edge. The shape and velocity distribution are shown in Fig. 1. The thickness is $29 \cdot 2$ per cent, the ratio of velocities at the slot is $1 \cdot 85$, and at the top of the C_L-range the velocity on the upper surface (expressed as a multiple of the stream velocity) is

$1 \cdot 808$. The point on the lower surface up to which the velocity distribution is flat at $C_L = 0$ turns out to be at only $0 \cdot 4$ chord from the nose. This is due merely to insufficient practical experience in technique at the time when the design was carried out, and the point could just as easily be brought back as far as it is in GLAS II. The porpoise-like quality of the aerofoil is entirely due to this unfortunate occurrence, and no significance should be attached to it. A much more serious failing is the fact that the value of C_{M_0} turns out to be $- 0 \cdot 16$, which is quite unthinkable. It is due to the lack of negative loading over the tail, and renders the design quite impracticable. This fault is corrected in the succeeding aerofoils.

GLAS II is the attempt to overcome the deficiencies noted above while leaving the general design unchanged. Near the trailing edge the velocity distribution is modified to give a smaller velocity on the upper surface than on the lower, and at the top of the C_L-range the velocity behind the slot is level instead of decreasing. Both these changes result in increased negative loading in the neighbourhood of the tail, and a C_{M_0} of 0 is achieved. A very low value of C_{M_0} is indispensable for aerofoils to be used in machines of the flying-wing type, so it is important to consider whether the required loading will be obtained in practice. The vital region is the extreme tail and it is here debatable whether the flow will be able to cope with the rather abrupt velocity changes occurring. Owing to the slot the boundary layer will be thin on the upper surface at least, and it seems reasonable to hope that the actual conditions will approximate closely to the potential flow. Even if the deviations are found by experiment to be significant it should then be possible to make a suitable compensating allowance in subsequent designs. The only other way to obtain negative loading appears to be to have an increasing velocity on the upper surface behind the slot. The gradient required to produce a worth-while effect is large while its attendant disadvantages are considerable, for it causes the tail to become unpleasantly thin as well as increasing the discontinuity at the slot, which is shown below to be unfavourable owing to its action in producing reflex curvature of the surface. Thus this process cannot be recommended.

The thickness of GLAS II is $31 \cdot 5$ per cent, the ratio of velocities at the slot is $3 \cdot 08$, and the upper surface velocity is $1 \cdot 901$ at the top of the C_L-range. Fig. 2 illustrates the shape and the velocity distribution. Since this aerofoil seems to be quite a reasonable example of the type which might be used in practice, a list of ordinates and a summary of its leading characteristics are given in Appendix I.

The aerofoil GLAS III is basically similar to GLAS II, having $C_{M0} = 0$, but the region of falling velocity on the lower surface is eliminated by the introduction of a second slot there. As a result a favourable velocity gradient is obtained at all points of the surface throughout the whole C_L-range. However, the ratio of velocities at this second slot is only $1 \cdot 334$, which is hardly sufficient to justify its existence. At the main suction slot the ratio is $3 \cdot 16$, and the maximum upper surface velocity is $1 \cdot 902$. The thickness is $31 \cdot 1$ per cent. The aerofoil and its velocity distribution are depicted in Fig. 3. It will be noted that the tail is very thin and bent up rather awkwardly; this is due to the difference between the upper and lower surface velocities in this region being greater than before.

In each of these three aerofoils there is a point very near the leading edge where the curvature has a logarithmic infinity; a result of the design technique of producing a velocity distribution flat right up to this point at the ends of the C_L-range. This has little importance within the C_L-range, but tends to limit the lifts obtainable outside it owing to the formation of a large suction peak near the nose. Accordingly, a process has been devised by which a leading-edge radius of curvature may be incorporated, and it is applied in the design of GLAS IV.

This aerofoil has a C_L-range extending over 18 deg. incidence, from $C_L = 0$ to $C_L = 2 \cdot 516$, and a thickness of $38 \cdot 3$ per cent. The slot is at $0 \cdot 70$ chord from the nose, the ratio of velocities being $4 \cdot 12$, and the velocity on the upper surface is $2 \cdot 052$ at the top of the C_L-range. In general, the velocity distribution is of similar type to that of GLAS II, but with two important modifications. The first, referred to above, results in removing the logarithmic infinity in the curvature of the surface near the nose, which is now well rounded with a leading-edge radius of curvature of about 0·05 chord. The second avoids the spiral at the slot by replacing the discontinuity in velocity by a steep adverse gradient over a short length of the surface. Whether this will appreciably affect the aerodynamic performance or the amount of suction required can be decided only by experiment. The shape and velocity distribution of GLAS IV are shown in Fig. 4, and a summary of the leading characteristics of the aerofoil is given in Appendix II. The requirement $C_{M_0} = 0$ is a somewhat stringent one for an aerofoil of this thickness and camber, and consequently the discontinuity at the slot is large, causing a very pronounced reflex curvature behind the slot, and the tail is rather thin and slightly upturned.

Discussion.—The most striking feature of these aerofoils is the vast C_L-range of 2·0, which may be compared with the C_L-range from $-0\cdot6$ to $+0\cdot6$ possessed by a symmetrical aerofoil of similar thickness designed by Goldstein's method, and described in Ref. 2. It is quite practicable to consider an aerofoil which in all normal flight conditions will be operating within its C_L-range, achieving laminar flow right up to the slot and consequently requiring only a small amount of suction to produce low-drag qualities. For a wing in which suction is applied over the centre-section only, when the incidence is 15 deg. and the suction aerofoil is at the top of its C_L-range, the outer sections, of conventional low-drag form, will be operating at a much higher C_L, aided by flaps or other high-lift devices. A split flap may also be fitted to the suction aerofoil itself. In any case there is no reason to suppose that even the value of 2·5 attained in GLAS IV is the limit of the C_L-range obtainable for an aerofoil of this type.

Most suction aerofoils previously considered have been fitted with two slots, but if a satisfactory performance can be obtained with only one a great saving and simplification will be achieved. In GLAS III, the only aerofoil of the present series with two slots, the discontinuity of velocity at the lower slot is very small, and it is clear that with aerofoils cambered to this extent the lower slot is quite redundant. Even in the case of aerofoils which are symmetrical or have a small amount of camber considerably less suction is required at the lower slot than the upper one, and the regulation of the suction in itself provides another complication. In none of the other aerofoils is the adverse velocity gradient on the lower surface excessive, so it may be concluded that for aerofoils of this type one slot only is definitely to be preferred.

All four aerofoils have a cusp at the trailing edge. This is the most convenient for design purposes and probably also gives the best low-drag qualities. From structural considerations a small radius of curvature may be preferable, and this would in addition restrain the tendency, noted above, for the tail to turn up and become unduly thin when there are considerable velocity changes in the vicinity.

The position of the slot is a matter for compromise. The further back it is on the chord the greater the area over which laminar flow may be expected, for behind the slot the boundary layer is certain to be turbulent owing to the concavity of the surface, and the greater the internal space available for stowage. The drawback is that the discontinuity of velocity at the slot rises and the curvature of the surface in the neighbourhood increases, as the slot is moved back. The effect is accentuated when a C_{M_0} of 0 is required, as the negative loading over the tail has to be concentrated into a smaller area.

This reflex curvature over the tail region produced by a large discontinuity at the slot seems certain to have a serious adverse effect on the flow obtained without suction. The result of suction failure is a vital question, particularly for a wing in which the suction is applied over the whole span, and experimental investigation is essential. But, it seems clear that the less curved the neighbourhood of the slot, the better is the chance that the airflow will rejoin the surface again afterwards. For example, GLAS I, in which the discontinuity is small, is appreciably superior to GLAS II in this respect. It is most desirable to limit the size of the discontinuity as far as possible, consistent with other design requirements.

The aerofoils of this paper all have their C_L-ranges starting at $C_L = 0$, and so, in flight, full advantage can be taken of the whole of the C_L-range. This appears greatly preferable to the case of symmetrical aerofoils, where half the C_L-range is effectively wasted. There are two disadvantages. To get $C_{M_0} = 0$ the discontinuity at the slot has to be rather large, which has been shown to be undesirable. Also the maximum velocity on the upper surface is such that the critical Mach number may be unacceptably low. It should be noted that the values given for the maximum velocity refer to flight at the top of the C_L-range ; at high speed the operating C_L will be much lower and the velocity will be appreciably less. The shock-wave will form first at the slot as this is the point where the maximum velocity is reached, and the danger of separation may be reduced by the sucking away of the boundary layer at this point. Thus it may be possible to fly at a considerably higher Mach number than appears likely at first sight.

A possible compromise is to take the bottom of the C_L-range at a small negative C_L instead of at $C_L = 0$. This reduces the amount of camber necessary to secure $C_{M_0} = 0$ and hence also the discontinuity, but it seems that only a very small diminution in maximum velocity is achieved while the thickness is considerably increased. Furthermore the adverse velocity gradient on the lower surface becomes worse, and it may be necessary to incorporate a second slot there to prevent separation. This has been seen to be an awkward and not very efficient complication. If the thickness is kept constant and a modification is effected by lowering the top and bottom of the C_L-range equal amounts, the discontinuity and maximum velocity are both appreciably reduced ; but this is scarcely a fair comparison as the top of the C_L-range is one of the most vital parameters on which the whole design is based. It appears in fact that a low critical Mach number is part of the price that must be paid to enjoy the full advantages of thick suction aerofoils.

REFERENCES

No.	*Author*	*Title, etc.*
1	Lighthill, M. J.	A New Method of Two-dimensional Aerodynamic Design. R. & M. 2112. April, 1945.
2	Richards, E. J., Walker, W. S. and Taylor, C. R.	Wind-tunnel Tests on a 30 per cent Suction Wing. R. & M. 2149. July, 1945.

APPENDIX I

Details of GLAS II

Ordinates

Lower Surface		Upper Surface	
x	y	x	y
0	0	0	0
0·00007	− 0·00229	0·00017	0·00290
0·00118	− 0·00680	0·00119	0·00861
0·00394	− 0·01096	0·00307	0·01475
0·00803	− 0·01519	0·00578	0·02123
0·01327	− 0·01947	0·02438	0·04954
0·01957	− 0·02376	0·05460	0·07988
0·02688	− 0·02805	0·09540	0·11036
0·03515	− 0·03231	0·14550	0·13935
0·04434	− 0·03654	0·20344	0·16546
0·08973	− 0·05272	0·26745	0·18749
0·14737	− 0·06720	0·33564	0·20427
0·21516	− 0·07930	0·40591	0·21523
0·29079	− 0·08846	0·47604	0·21929
0·37179	− 0·09422	0·54363	0·21589
0·45550	− 0·09612	0·60606	0·20421
0·53921	− 0·09372	0·65963	0·18276
0·61999	− 0·08588	0·67089	0·17549
0·69844	− 0·07080	0·68088	0·16719
0·77532	− 0·05251	0·68878	0·15755
0·84703	− 0·03484	0·69196	0·15225
0·87964	− 0·02701	0·69248	0·14920
0·90937	− 0·02012	0·69109 —Slot—	0·14684
0·93562	− 0·01427	0·68681	0·13957
0·95792	− 0·00949	0·68840	0·13018
0·97574	− 0·00571	0·69819	0·11385
0·98881	− 0·00279	0·71954	0·08773
0·99705	− 0·00071	0·74436	0·06715
1·00000	0	0·77000	0·05065
		0·82047	0·02677
		0·86681	0·01176
		0·90727	+ 0·00298
		0·94091	− 0·00135
		0·96723	− 0·00268
		0·98591	− 0·00205
		0·99669	− 0·00061
		1·00000	0

Characteristics

Thickness 31·5 per cent.
C_L-range $C_L = 0$ to $C_L = 2\cdot004$ (corresponding to an incidence range of 15 deg.).
$C_{M_0} = 0$

Theoretical lift-curve slope	7·743
No-lift angle	− 1 deg. 49 min.
Aerodynamic centre	$x = 0\cdot3077$
Maximum velocity at $C_L = 2\cdot004$	$q = 1\cdot901$
Maximum velocity at $C_L = 0$	$q = 1\cdot750$
M_{crit}	0·458
Position of suction slot	$x = 0\cdot6911$
Ratio of velocities at slot	3·081 : 1

APPENDIX II

Details of GLAS IV

Ordinates

Lower Surface		Upper Surface		
x	y	x		y
0	0	0		0
0·00004	— 0·00191	0·00110		0·00979
0·00154	— 0·01296	0·00461		0·02220
0·00565	— 0·02336	0·01820		0·04900
0·01238	— 0·03313	0·03969		0·07739
0·02175	— 0·04228	0·06838		0·10626
0·03383	— 0·05086	0·10363		0·13468
0·06563	— 0·06698	0·14472		0·16180
0·10632	— 0·08169	0·19085		0·18683
0·15465	— 0·09468	0·24113		0·20910
0·20941	— 0·10560	0·29458		0·22801
0·26935	— 0·11416	0·35013		0·24298
0·33313	— 0·12009	0·40669		0·25359
0·39940	— 0·12315	0·46307		0·25944
0·46673	— 0·12308	0·51805		0·26020
0·53363	— 0·11959	0·57033		0·25557
0·59851	— 0·11187	0·61845		0·24524
0·66210	— 0·09846	0·66053		0·22866
0·72551	— 0·08175	0·69310		0·20467
0·78706	— 0·06409	0·69614		0·20103
0·84478	— 0·04712	0·69883		0·19723
0·89640	— 0·03207	0·70109		0·19324
0·93959	— 0·01968	0·70278		0·18908
0·95733	— 0·01458	0·70364		0·18476
0·97213	— 0·01019	0·70288		0·18063
0·98383	— 0·00641	0·70206		0·17966
0·99242	— 0·00316	0·70073	—Slot—	0·17842
0·99799	— 0·00087	0·69883		0·17670
1·00000	0	0·69655		0·17386
		0·69358		0·15752
		0·69697		0·14114
		0·70327		0·12601
		0·71136		0·11215
		0·72062		0·09950
		0·76336		0·05899
		0·80853		0·03139
		0·85168		0·01308
		0·89075		+ 0·00194
		0·92457		— 0·00396
		0·95257		— 0·00615
		0·97440		— 0·00551
		0·98941		— 0·00311
		0·99754		— 0·00091
		1·00000		0

Characteristics

Thickness 38·3 per cent.

C_L-range $C_L = 0$ to $C_L = 2{\cdot}516$ (corresponding to an incidence range of 18 deg.).

$C_{M0} = 0$

Theoretical lift-curve slope	8·14
No-lift angle	— 1 deg. 29 min.
Maximum velocity at $C_L = 2{\cdot}516$	$q = 2{\cdot}052$
Maximum velocity at $C_L = 0$	$q = 1{\cdot}889$
M_{crit}	0·421
Position of suction slot	$x = 0{\cdot}701$
Ratio of velocities at slot	4·117 : 1

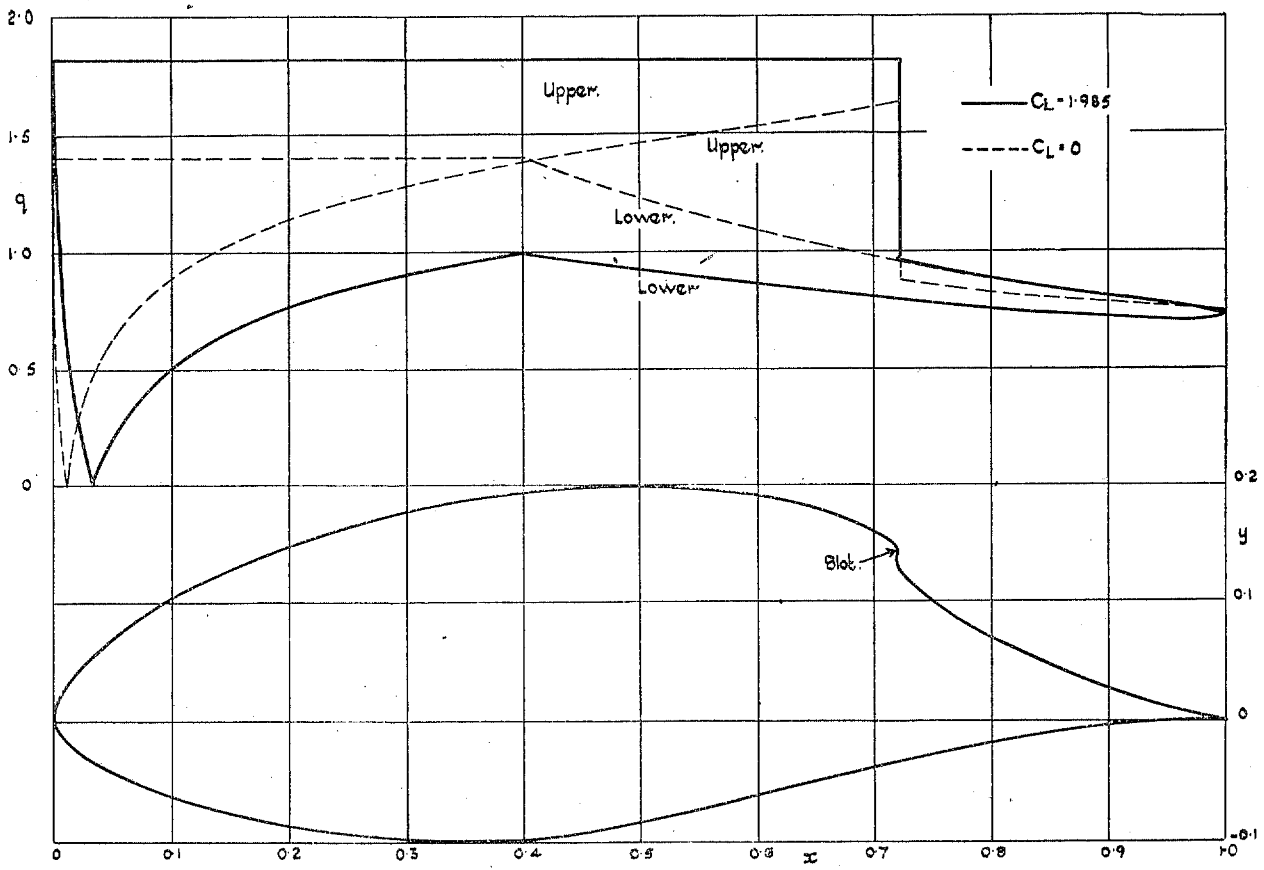

Fig. 1.—GLAS I.

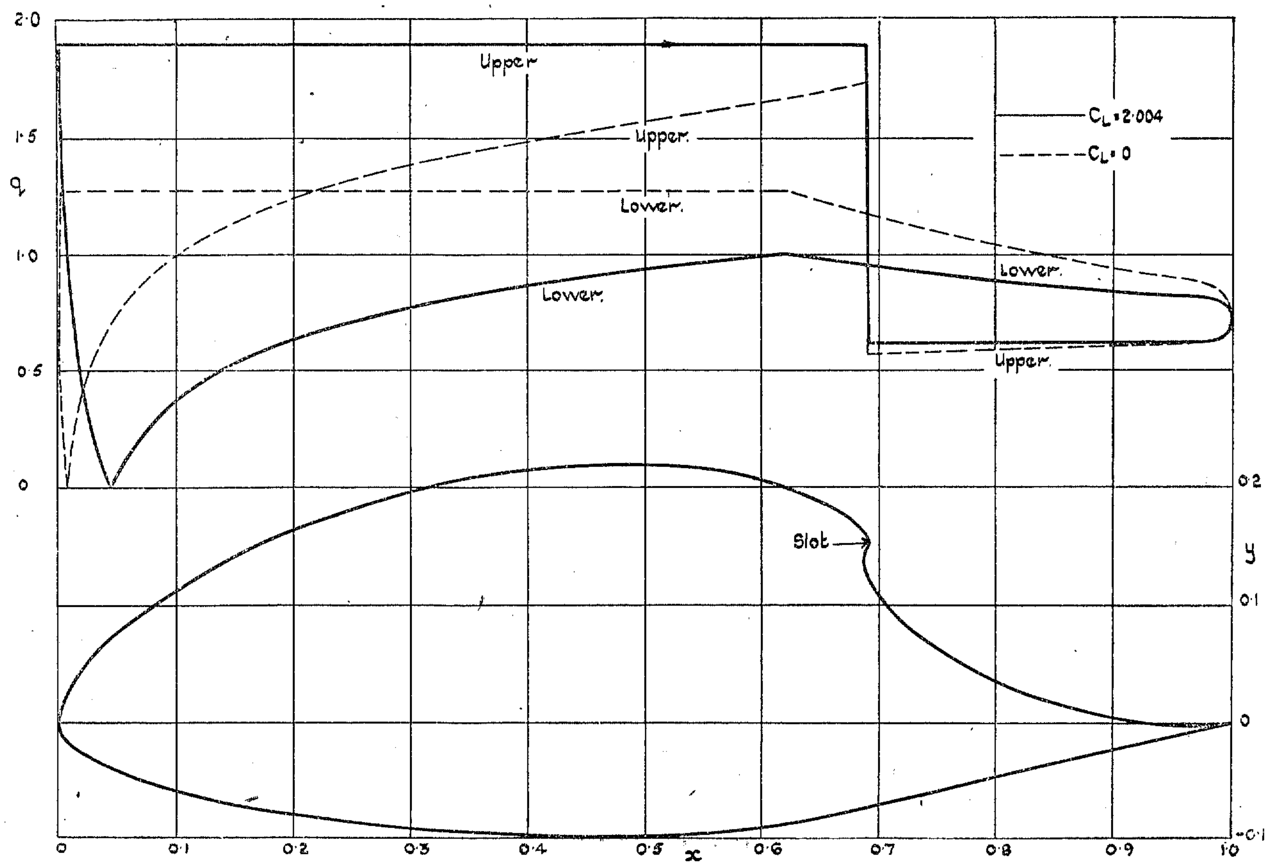

Fig. 2.—GLAS II.

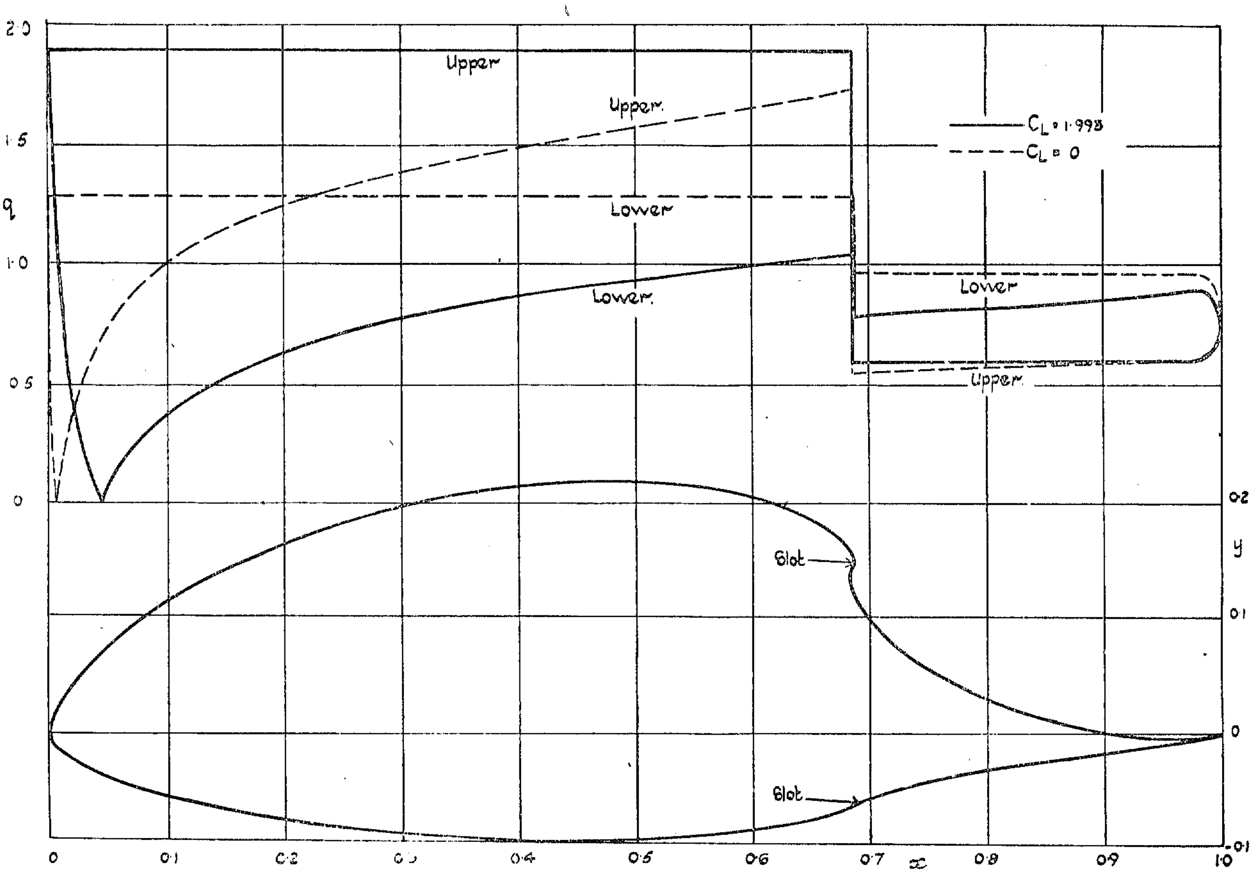

FIG. 3.—GLAS III.

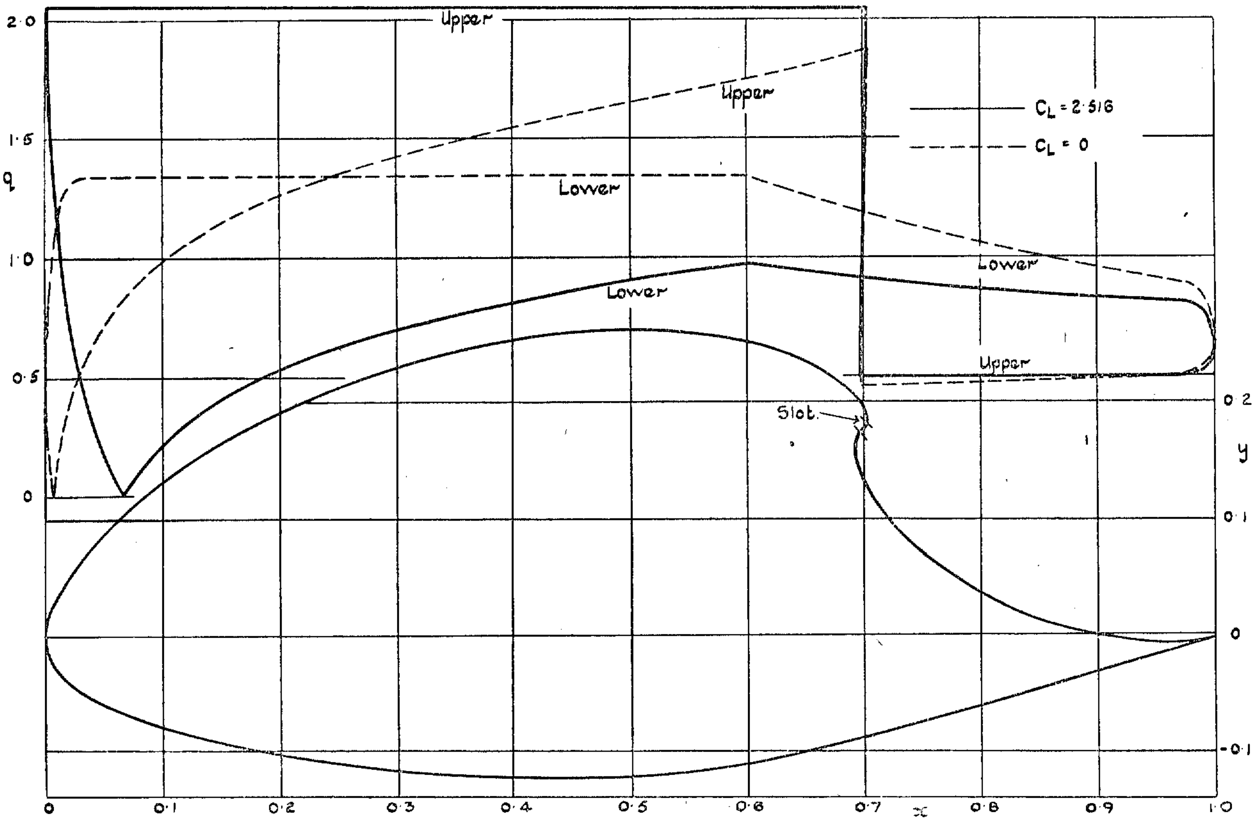

FIG. 4.—GLAS IV.

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