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Notes on the Tail-first Aeroplane

By

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Summary.—The tail-first aeroplane has certain strong attractions when combined with a tricycle undercarriage; in particular it has been suggested that it would represent a definite advance in the production of high lift.

In these notes the main characteristics of a tail-first design are summarised and discussed, and an analysis is given of high-lift control with front and rear tails. It is shown that the high-lift claims made for the front tail are illusory in the present stage of development of high lift devices, owing to the high lift which the tail must provide to balance the high lift of the wing.

A front tail would immensely simplify the problem of longitudinal stability. The problem of getting enough directional stability and control without increasing drag would require research on a model. It could probably be arranged to work with a $C_{L\,\max.}$ of from 2 to 2·5 (*i.e.*, with full-span slotted or split flaps), but is incapable of dealing with a $C_{L\,\max.}$ of 3 or over unless the point of application of high lift can be moved much further forward on the wing chord than at present.

Introduction.—The tail-first aeroplane has been mooted as an attractive way out of several of the difficulties which hamper multi-engine design; particularly where high lift is a major consideration. It is the intention in these notes to make a list of the advantages which are claimed for the front tail and to examine critically the prospect of realising longitudinal control with high lift.

The main advantages claimed for the tail-first scheme may be summarised as follows :—

(a) Removal of the tail from the complex air flow behind wing nacelles makes its characteristics much more predictable, improves its efficiency, and immensely simplifies problems of longitudinal stability and control. With the rear tail, freedom in detailed design of wing engines is hampered because, while the designer knows that the destabilising effect of the slipstream may be very serious, research on the subject has not gone far enough to give him control of the factors involved. These anxieties would disappear with the adoption of the front tail.

(b) The tricycle undercarriage is uneconomical with a rear tail for two reasons, each of which indicates that it would be a natural development to place the tail over the nose wheel :—

  (1) The nose wheel brings a considerable addition to total weight in a conventional design. With a front tail, weight can be saved through the more economical relation of inertia loads to air loads in landing, and also by curtailment of the rear body.

  (2) In a conventional design the landing incidence is severely limited unless the angle of wing to body is adjustable. This prevents the use of any high-lift device, such as the leading edge slot, which works by prolonging the lift curve. There is no reason why, with the advent of the nose wheel, this limitation should be perpetuated. If the rear body length is halved the incidence available before touch down can be raised to 30 deg.

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* R.A.E. Report B.A.1542—received 18th November, 1941.

(c) In their present stage of development, high-lift devices add lift considerably behind the centre of gravity. Part of this is lost by the negative balancing lift on the rear tail. If a $C_{L\,\text{max.}}$ of 3 is aimed at, $0 \cdot 3$ may be lost in this way. Thus there would be a net gain in $C_{L\,\text{max.}}$ of the order $0 \cdot 5$ with a front tail, which adds lift instead of subtracting it.

(d) The nose-down pitching moment induced by the ground on the rear tail is a serious consideration in landing with very high lift, unless it is proposed to fly straight into the ground. Most of this would disappear with a front tail.

(e) Burying the engines in the wings means a backward shift of centre of gravity which cannot at all easily be balanced by weight forward in the conventional design and may lead to excessively high rear tail volumes. It is claimed that the centre of gravity problem in this development becomes much easier with a front tail layout, where use is made of a cabin extending to the tail and housing large weights forward of the wing.

If the above features can be successfully combined, the tail-first aeroplane would land at a C_L approaching $1 \cdot 0$ in excess of the optimum for the rear tail ($0 \cdot 5$ from increased incidence, $0 \cdot 5$ from reversal of tail lift), and the ground effect on tail moment would no longer be unfavourable. Tail efficiency would be improved, longitudinal stability would be much more accurately predictable, and there would probably be a saving in structural weight. The question remains, is this prospect realisable ? Two main objections to it, on the score of (a) directional stability and (b) longitudinal control with high lift, will now be examined.

Directional Stability.—An objection commonly advanced against the front tail is the difficulty of getting enough directional stability without a large increase of surface relative to the rear tail arrangement. A very rough view of the problem is given by the following considerations. It will certainly be convenient, if not actually dictated by operational and housing requirements, to carry the body right forward to the front tail. Assuming this, it is probable that front and rear tail layouts to the same specification would show bodies of about the same length, the difference being that in relation to the centre of gravity the front-tail body would be shifted perhaps a quarter of its length forward while the wings would be shifted a third-chord back. It would be quite unnecessary to give the front-tail design as much weathercock stability as is now a common but rather adventitious feature of the conventional layout; and the backward shift of the wings would balance to some small extent the forward shift of the body. In all probability a large fin, with some small increase in drag, would be inevitable, but the point can only be settled by model work. The rudder would of course be placed at the rear to ease the stability problem; and it too would necessarily be larger than usual. As far as can be seen, the tail-first design would tend in its lateral qualities to revert to types of fifteen years ago, with small weather-cock stability and the rudder the leading control. Its spinning characteristics can hardly be predicted, but could easily be explored on a model.

Longitudinal Control.—The essential difference between the front and the rear tail can be seen by considering the simple case in which wing and tail are symmetrical aerofoils which stall at the same angle. If the stability is neutral the tail setting will be constant and zero for all incidences of the system, but as the front tail works in a small upwash and the rear tail in a large downwash, the front tail will stall slightly before the wing and the rear tail considerably after it. If there is positive stability this difference is increased, because now the front tail must be set at an increasingly positive angle as the wing incidence increases, and the rear tail at an increasingly negative angle.

The basic problem of front-tail design is therefore to get enough lift coefficient out of it to balance the highest lift coefficient which is contemplated on the wing. If the latter is normal, say $C_{L\,\text{max.}} = 1 \cdot 5$, the problem is easily soluble by using an ordinary elevator. But if high lift of the order $C_{L\,\text{max.}} = 3$ is contemplated, and if the added lift provides a large nose-down pitching moment, the conditions become very difficult to satisfy. As this is a crucial aspect of the subject, an analysis will be given in full. In what follows, the downwash on the wing from a tail in any position is neglected.

Suppose that an increment $\triangle C_L$ to the wing lift coefficient C_L at constant incidence requires a change of tail lift coefficient without interference from C_L' to $C_L' + \triangle C_L'$. Assume that the change in downwash at the tail is $(d\varepsilon/dC_L)\triangle C_L$ where $d\varepsilon/dC_L$ is the downwash slope before the addition of $\triangle C_L$. $d\varepsilon/dC_L$ is positive for a rear tail and small and negative for a front tail. Let $\delta C_L'$ be supplied by tail adjustment, so that we have

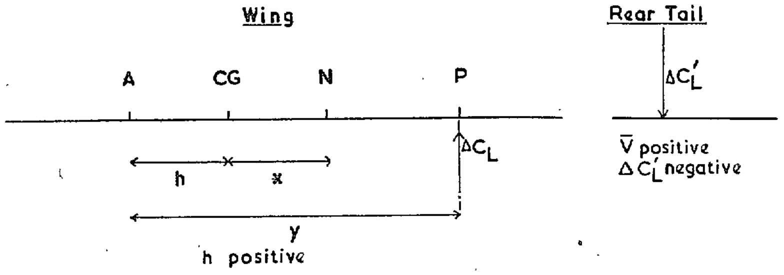
$$\triangle C_L' = \delta C_L' - a_1 \frac{d\varepsilon}{dC_L} \triangle C_L ,$$

and let $\delta_{\eta T}$ be the change in tail setting when the tail is rotated as a whole.

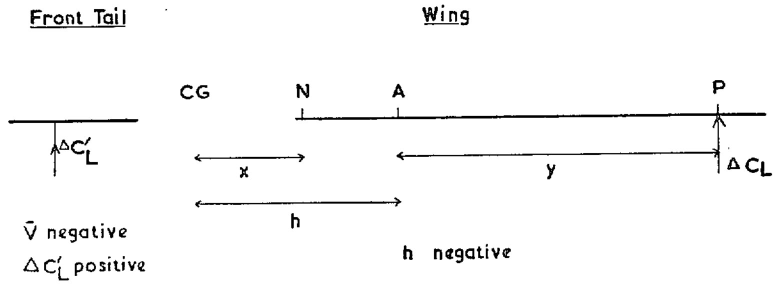
$\triangle C_L$ acts at P, yc behind the aerodynamic centre A; the centre of gravity is hc behind A and xc in front of the neutral point N. Thus x measures the stability; h is in general positive with a rear tail and negative with a front tail; and y, with the high-lift devices contemplated at present, is always positive. N is in front of A with a front tail and behind A with a rear tail. The tail volume $\bar{V}$ is defined to be positive for a rear tail and negative for a front tail, and E, the tail efficiency, is assumed to be unchanged by the addition of ΔC_L.

a and a_1 are respectively the lift slopes $dC_L/d\alpha$, $dC_L'/d\alpha'$ for wing and tail.

The positions of the various points defined above are sketched below for rear and front tail systems which are stable (x positive).



Rear Tail Arrangement



Front Tail Arrangement

With the above definitions the following equations apply to a tail in any position:—

$$C_{Mo} + hC_L = E\bar{V}C_L' , \text{ normal lift} \quad \ldots \quad (1)$$

$$(h - y)\triangle C_L = E\bar{V}\triangle C_L' = E\bar{V}\left(\delta C_L' - \frac{a_1}{a}\frac{d\varepsilon}{d\alpha}\triangle C_L\right), \text{ high lift} \quad \ldots \quad (2)$$

$$h + x = E\bar{V}\frac{a_1}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right), \text{ stability} \quad \ldots \quad (3)$$

These give the following expressions for tail lift in terms of x and y

$$C_L' = C_L \left\{\frac{a_1}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right) - \frac{x}{E\bar{V}} + \frac{C_{M_0}}{E\bar{V}}\right\} \quad \ldots \qquad (4)$$

$$\triangle C_L' = \triangle C_L \left\{\frac{a_1}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right) - \frac{x + y}{E\bar{V}}\right\} \quad \ldots \qquad (5)$$

$$\delta C_L' = a_1 \delta_{\eta T} = \triangle C_L \left(\frac{a_1}{a} - \frac{x + y}{E\bar{V}}\right) \quad \ldots \qquad (6)$$

$$C_L' + \triangle C_L' = (C_L + \triangle C_L)\frac{a_1}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right) - \frac{x(C_L + \triangle C_L) + y\triangle C_L - C_{M_0}}{E\bar{V}} \quad \ldots \qquad (7)$$

It follows from equations (4) to (7) that if the system is stable and high lift is added behind the aerodynamic centre, then

$$\frac{C_L'}{C_L},\ \frac{\triangle C_L'}{\triangle C_L},\ \frac{\delta C_L'}{\triangle C_L} \text{ and } \frac{C_L' + \triangle C_L'}{C_L + \triangle C_L} \text{ will all be } > \text{ or } < \frac{a_1}{a}$$

according as the tail is a front or rear one. a_1/a is the ratio of the increments in tail and wing lift coefficients when the incidence changes, each surface acting alone.

Tail conditions for normal lift.—These are given by equation (4), from which Fig. 1 is plotted, using $a_1/a = 0{\cdot}7$, $C_{M_0} = 0$, and $d\varepsilon/d\alpha = 0{\cdot}5$ for a rear tail and zero for a front tail.

In Fig. 1, $E\bar{V}$ is plotted against x for constant values of C_L'/C_L, the upper and lower halves of the diagram referring respectively to rear and front tails. It shows that at $E\bar{V} = \pm 0{\cdot}5$ and x between 0 and 0·1, values of C_L'/C_L between 0·15 and 0·35 are required for a rear tail, and between 0·7 and 0·9 for a front tail. Thus a front tail of average size requires a lift coefficient of the order 1·1 to balance a $C_{L\,\max.}$ of 1·5 if the system is to be stable. Rather more than this can be obtained from an ordinary tail-plane and elevator, but there is clearly little margin to balance higher lift.

Tail conditions for high lift.—A convenient rough survey of the high-lift problem is given by using equation (6) to plot $E\bar{V}$ against $x + y$ as constant values of $\delta C_L'/\triangle C_L$ or $\delta_{\eta T}/\triangle C_L$. This is shown in Fig. 2, in which each line is labelled with an unbracketed figure ($\delta C_L'/\triangle C_L$) and a bracketed figure ($\delta_{\eta T}{}^\circ/\triangle C_L$), using $a_1/a = 0{\cdot}7$ and $a_1 = 0{\cdot}06$ per deg. A vertical scale of $h + x$ is added from equation (3), using $d\varepsilon/d\alpha = 0{\cdot}5$ for a rear tail and $d\varepsilon/d\alpha = 0$ for a front tail.

If the tail volume $E\bar{V}$, the stability x and the point of application y of high-lift $\triangle C_L$ are known, they define a point on the diagram from which may be estimated the additional lift coefficient $\delta C_L'$ which is required by tail adjustment and the corresponding change of tail setting $\delta_{\eta T}$ on the assumption that the tail is rotated as a whole.

Consider for instance the possibility of balancing a $\triangle C_L$ of 2, which, from recent Royal Aircraft Establishment tests of large rearward moving flaps, is taken to act at about half-chord behind the aerodynamic centre ($y \doteq \frac{1}{2}$). The broken line on the diagram shows this value of y; positive stability x will shift it to the right, negative to the left. The diagram shows that a rear tail volume $E\bar{V}$ of about 0·75 would give no change of trim, while $E\bar{V}$ of 0·5, with $\delta C_L'$ about $-$ 0·6 and $\delta_{\eta T}$ about $-$ 10 deg., is quite workable (A on diagram). A front tail volume of 0·5 would have to provide, on the other hand, a $\delta C_L'$ of about 3·5 with a change in tail setting of at least 50 deg. (B on diagram). The diagram in fact shows at a glance that no front tail of reasonable volume can be made to work in the conditions specified. Assuming as a rough round figure that $\delta C_L'$ of $\pm$ 1 is the most that can be got out of the tail, the shaded area in the diagram shows the conditions in which a $\triangle C_L$ of 2 can be balanced; and the general conclusion is that if a front tail of normal area is to balance a $\triangle C_L$ of 2, the added lift must act in front of the aerodynamic centre, and conversely for the rear tail.

Fig. 2 demonstrates in a rough way the limitations of the front tail in balancing high lift, and the necessity of making the front tail itself a high-lift one if it is to work at all with a high-lift wing. We can assess more closely the limits of front tail capacity by calculating from equation (7) the high lift which can be balanced by a tail of given maximum lift coefficient $C_L' + \triangle C_L'$. A normal tail will give a coefficient of at least 1·5; 2·5 could be reached by applying the same high-lift devices as are now being tested; and 3·5 is not impossible. Figs. 3 to 5 have been prepared to illustrate the front tail performance with these values, using also $a_1/a = 0{\cdot}7$, $d\varepsilon/d\alpha = 0$, $C_{Mo} = 0$. Here it is assumed that the high-lift $\triangle C_L$ comes on at $C_L = 1$. $\triangle C_L$ is plotted against y for constant values of $E\bar{V}$ and x. Thus any curve of these diagrams shows the high lift which can be balanced by a front tail of given lift coefficient, volume and stability.

To complete the survey we can plot on these diagrams the characteristics of typical high-lift devices; the following are drawn from various British and American model tests of full-span flaps without boundary-layer control

Type	$\triangle C_L$	y	*Symbol in Figs.* 3 *to* 5
Plain flap	0·8	0·24	⊗
Split flap			
Slotted flap	0·8	0·30	⊕
Fowler	1·9	0·44	□
Double Fowler	2·4	0·44	●

Fig. 3 shows that the normal tail of reasonable volume can only balance split and slotted flaps if the system is unstable and is quite incapable of dealing with the Fowler flap. The high-lift tail giving 2·5 (Fig. 4) is still unable to balance the Fowler flap at a volume of less than 2. It is only when the tail lift is 3·5 (Fig. 5) that the Fowler lifts can be dealt with at a reasonable tail volume, and then only when the system is unstable.

It appears in fact from a consideration of these diagrams or of equation (7) that a front tail of reasonable volume, say 0·5, must have $C_L' + \triangle C_L'$ considerably greater than $C_L + \triangle C_L$ if y is greater than a quarter and the system is stable. In other words a front tail of reasonable volume must be fitted with a more powerful high-lift device than is used on the wing. Thus it should not be difficult to arrange a front tail to balance full-span flaps which do not move back, but there is small prospect of balancing the highest lifts obtainable by rearward moving flaps; the front tail is a practical proposition for a $C_{L\,\mathrm{max.}}$ of 2 to 2·5, but not for 3 or over.

Alternatively, it can be said that a front tail can only balance a $\triangle C_L$ of 2 which acts much further forward than with the high-lift arrangements at present tested; and the prospect of obtaining high lift near the aerodynamic centre is rather remote. There remains of course the possibility of relying mainly on a prolongation of the lift curve; but in that case the front tail would have to be fitted with the same device as the wing.

Correction for Downwash of Front Tail on Wing.—It should be noticed that this calculation is favourable to the front tail in that it neglects its mean downwash ε_w on the wing. If this is included, equation (3) becomes

$$(h + x)\left(1 - \frac{d\varepsilon_w}{d\alpha}\right) = E\bar{V}\,\frac{a_1}{a}\left(1 - \frac{d\varepsilon}{d\alpha}\right)$$

and in equation (7) we can replace $1 - d\varepsilon/d\alpha$ by $1 - d\varepsilon/d\alpha + d\varepsilon/d\alpha_w$ approximately. Thus the additional tail lift to balance $C_L + \triangle C_L$ at given values of x and y is

$$(C_L + \triangle C_L)\,\frac{a_1}{a}\,\frac{d\varepsilon_w}{d\alpha}$$

$d\varepsilon_w/d\alpha$ is a function of the tail volume and increases with it. For reasonable tail volumes, *e.g.*, between 0·5 and 1, $d\varepsilon_w/d\alpha$ is unlikely to be greater than 0·15. Hence the tail lifts shown in this calculation are probably about 10 per cent. too low. The general argument is not invalidated but if tail volumes greater than 1 are being considered a more elaborate analysis would be necessary.

It should also be noticed that the wash from the front tail would tend to stall the outer portions of the wing and might limit to some small extent the maximum lift attainable. This should not affect materially the results of Figs. 3 to 5, where high lift is supposed to be applied well below the stall.

Conclusions.—(1) The front tail is very attractive because its characteristics would be predictable and free from the complex slipstream effects on the rear tail, thus immensely simplifying the longitudinal stability problem.

(2) There is no *a priori* reason why a front tail design should not be arranged to give enough directional stability and control without a large increase in drag, but model work would be necessary to examine both this and its spinning qualities.

(3) The argument that a front tail is particularly suitable in high-lift design breaks down because of the high lift which it must supply for balance. In the present stage of high-lift flap development, the high lift acts at a considerable distance behind the aerodynamic centre, and a front tail of reasonable volume must have a $C_{L\,\mathrm{max.}}$ greater than the $C_{L\,\mathrm{max}}$ of the wing. Thus a front tail must be fitted with a more powerful high-lift device than is fitted to the wing. The problem of balancing the highest lifts thus becomes insoluble:—a front tail could be arranged to balance full-span slotted or split flaps, but not the highest lift associated with Fowler and double-flap developments.

(4) The front tail has many attractions in combination with the tricycle undercarriage. It would be a feasible proposition with moderate $C_{L\,\mathrm{max.}}$ (2 to 2·5), but the advantages claimed for it at $C_{L\,\mathrm{max.}}$ of 3 or more are illusory.

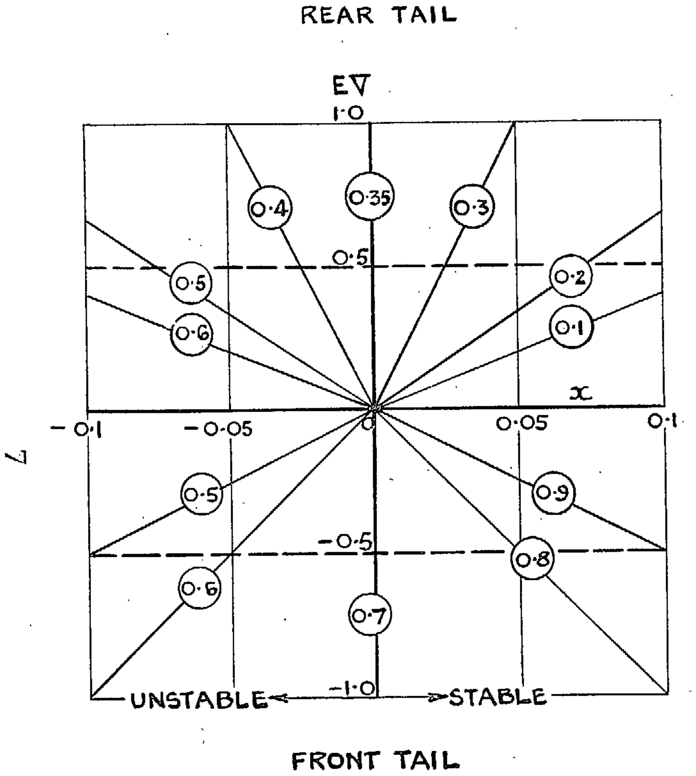
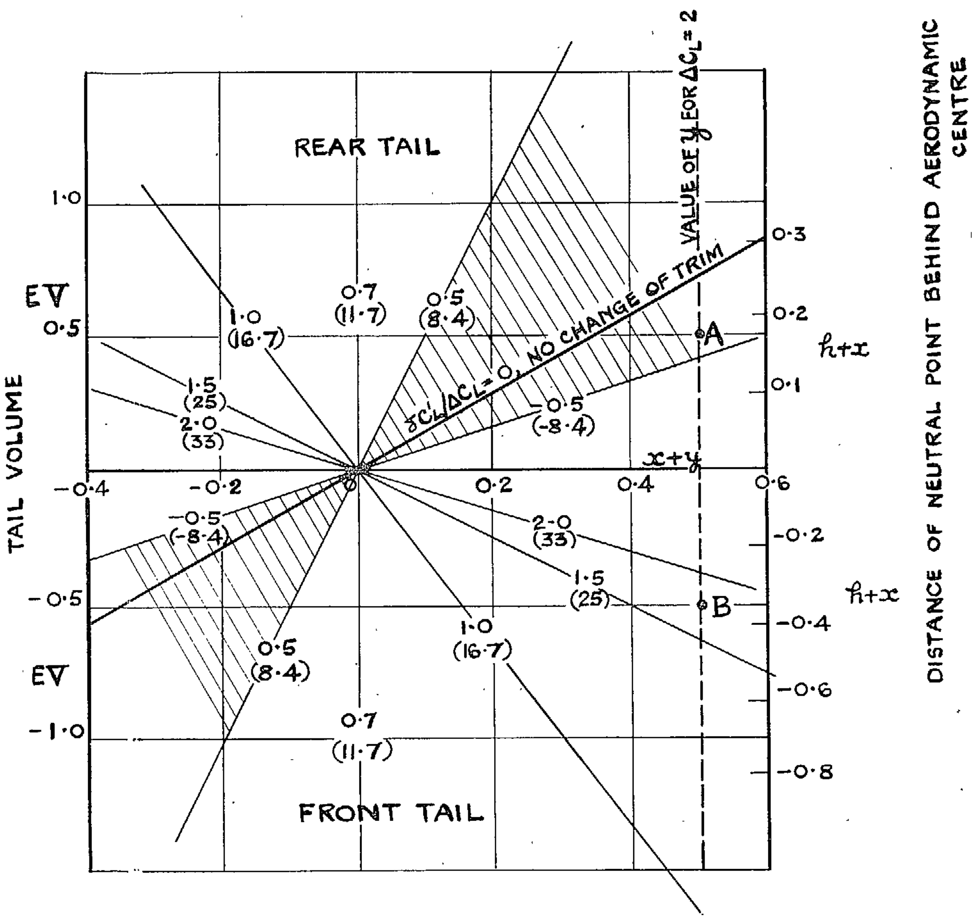


FIG. 1. Tail condition with normal lift—the curves are labelled with values of C_L'/C_L.



Unbracketed numbers are values of $\delta C_L'/\triangle C_L$.
Bracketed numbers are values of $\delta\eta_T^\circ/\triangle C_L$.
Practical region for balancing $\triangle C_L = 2$ is shaded.

FIG. 2. Tail condition with high lift.

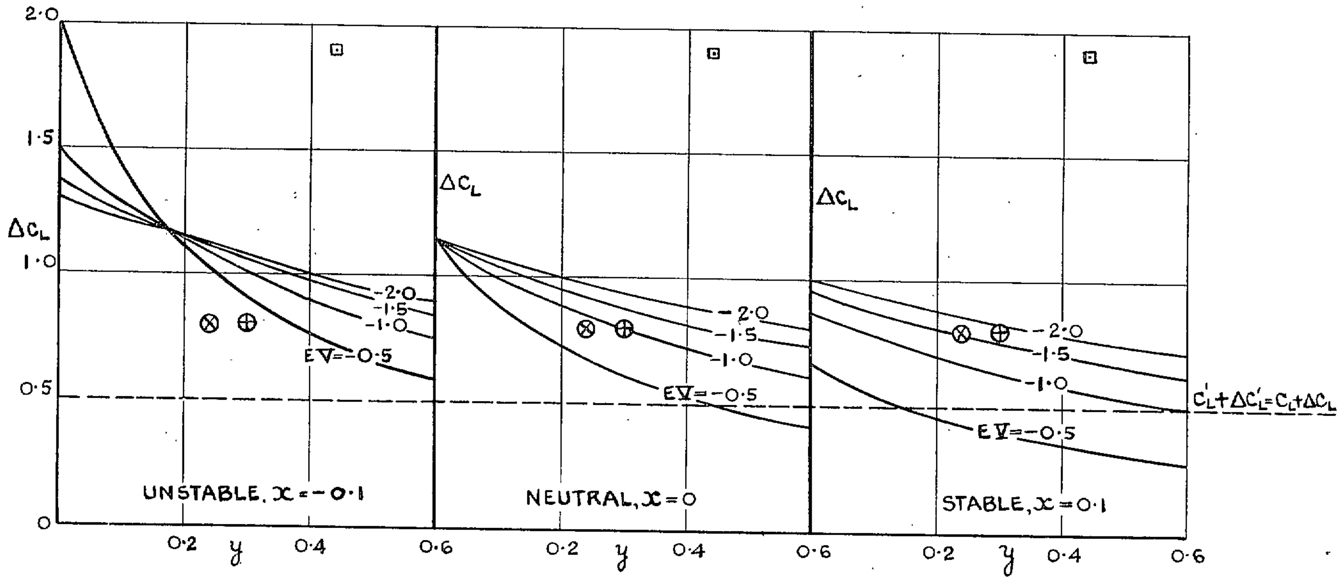


FIG. 3. Front tail capacity with high lift added at $C_L = 1$.

Normal tail, $C_L' + \triangle C_L' = 1{\cdot}5$.

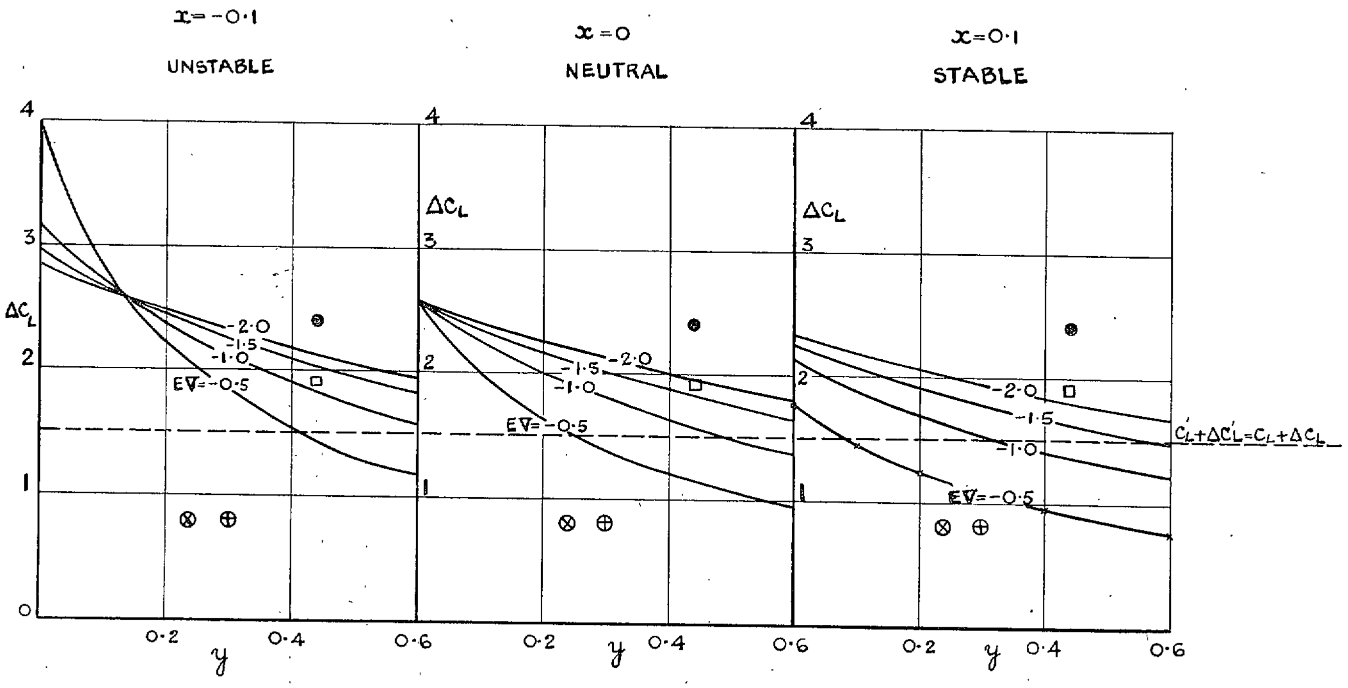


FIG. 4. Front tail capacity with high lift added at $C_L = 1$.

High-lift tail, $C_L' + \triangle C_L' = 2{\cdot}5$.

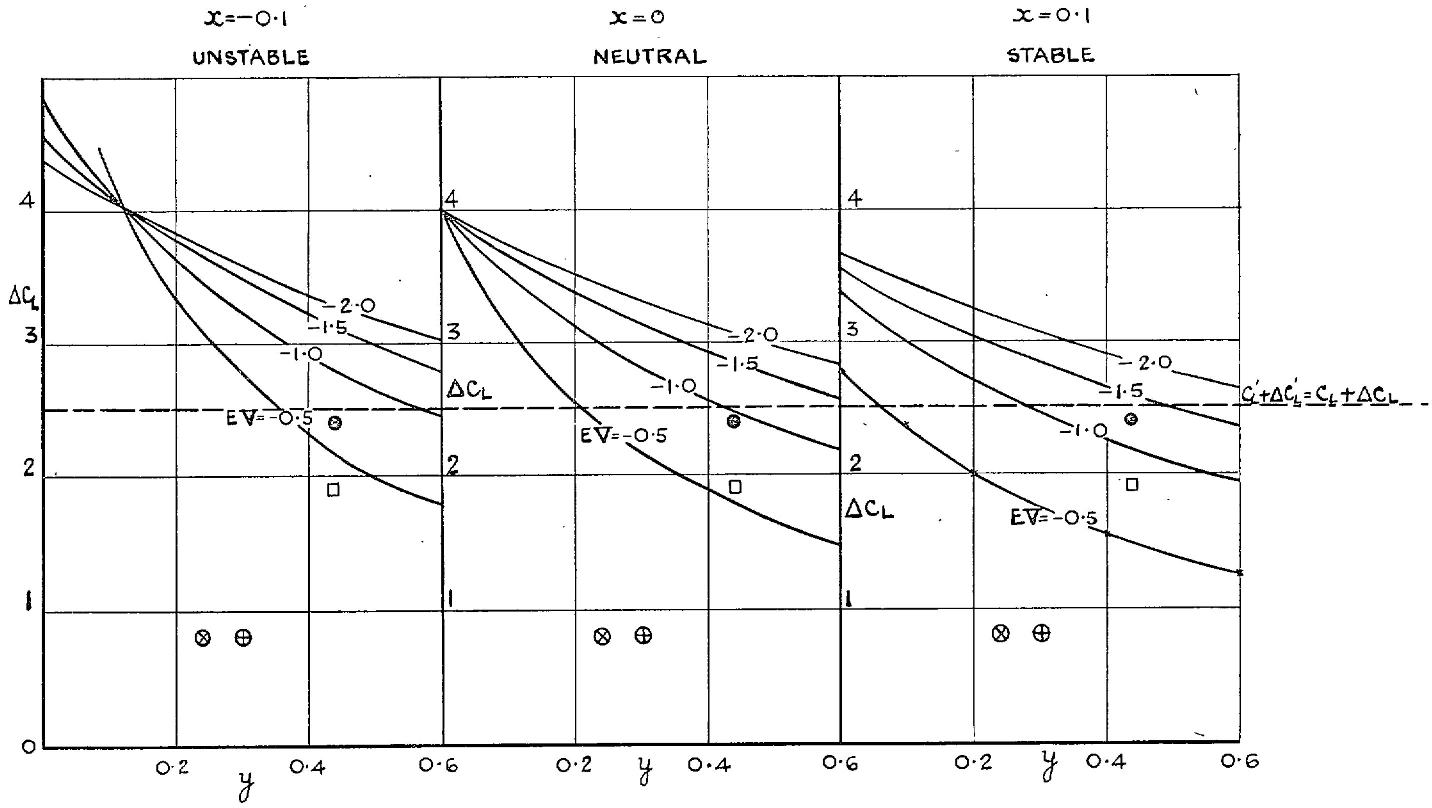


FIG. 5. Front tail capacity with high lift added at $C_L = 1$.

High-lift tail, $C_L' + \triangle C_L' = 3{\cdot}5$.

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