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Lateral Control with High Lift Devices

By

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WITH APPENDIX BY R. R. DUDDY, B.Sc.

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Lateral Control with High Lift Devices

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COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR),
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Summary.—Reasons for Enquiry. The increasing attention which high-lift devices are receiving makes it desirable that a summary of the present information on lateral control with high-lift devices should be available.

Range of Investigation.—The devices considered are classified as—

(A) those devices that can be used with full span flaps; these include
  (i) spoilers,
  (ii) auxiliary aerofoils,
  (iii) ailerons behind Zap type flaps,
  (iv) ailerons behind slotted flaps,

and (B) those devices which can be used only with nearly full-span flaps and which include
  (i) short span, wide chord ailerons (straight and skew hinge),
  (ii) floating tip ailerons,
  (iii) ailerons formed from part of rear flap of large double-slotted flap.

Conclusions.—A brief summary of the main characteristics of the various devices considered is found in Table 1. No satisfactory method of lateral control has yet been developed that permits full use of the high-lift devices covering the complete wing span, although there is a reasonable hope that a satisfactory spoiler control will yet be developed. For the present, methods of lateral control must be accepted which restrict to some extent the span or type of flap; a number of such methods which are fairly satisfactory are available. The loss of possible lift increment incurred in their use need not be greater than about 15 per cent. of the increment due to full-span flaps.

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1. *Introduction.*—High lift devices involve full span or nearly full-span flaps and hence, in general, cannot be used in conjunction with the conventional type of aileron. It follows that the successful application of high-lift devices requires the satisfactory development of some alternative form of lateral control not requiring a large proportion of the wing span to the exclusion of the flap. A number of such devices have been examined both here and in America; none of these devices have as yet been applied to production aeroplanes, but a number show considerable promise. Since high-lift devices are now attracting the increasing attention of designers, it was considered desirable to prepare a summary of the existing information on these various alternative forms of lateral control.

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* R.A.E. Report B.A. 1659, received 15th June, 1941.

The forms of lateral control which have been considered in this note can be classified as those which can be used with full span flaps and those which can be used only with nearly full-span flaps. Under the former heading are considered the following:—

1. Retractable-arc spoilers.
2. Hinged flap spoilers (including slot lip ailerons).
3. Controllable auxiliary aerofoils.
4. External ailerons.
5. Upper surface ailerons.
6. Narrow chord ailerons (behind Zap type flap).
7. Plain ailerons behind full-span slotted flap.

Under the heading of controls for use with part-span flaps are considered:—

1. Short span ailerons (straight and skew hinge).
2. Combinations of short-span ailerons and spoilers.
3. Floating tip ailerons.
4. Outer parts of rear flap of large N.A.C.A. double-slotted flap used as ailerons.

A summary of the main characteristics of the various devices considered is found in Table 1.

2. *Lateral Control.—General.*—Ordinary ailerons have certain qualities which are generally recognised as desirable and it is to be assumed that any alternative system of control must possess these qualities to be considered satisfactory. These qualities are

(*a*) prompt response, *i.e.* absence of objectionable lag or sluggishness,

(*b*) even increase of response with stick movement,

(*c*) even increase of stick force with stick movement,

(*d*) adequate rolling action up to the stall,

(*e*) ability to be balanced sufficiently to avoid heavy stick forces.

In addition, other features which are probably desirable, but which are not as a rule possessed by ordinary ailerons, are

(*f*) small and favourable yawing moments, particularly at high angles of incidence,

(*g*) appreciable rolling action beyond the stall.

The examination of the various lateral control devices considered has, therefore, been made in the light of the above requirements. Hence, some general remarks enlarging on these requirements will be of value at this stage.

The lag is defined as the time that elapses after a control is moved before the aeroplane begins to respond to the movement. A control is usually referred to as sluggish if once rolling has begun the rolling moment builds up to its full value at a rate slow enough to be objectionable to the pilot. Therefore, the sluggishness is conveniently, if roughly, measured by the time that elapses (less any lag) after the control has been displaced before the rolling moment reaches its full value.*

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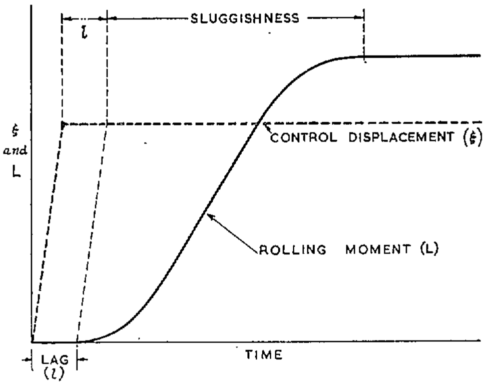
* This definition is perhaps not completely satisfactory since it is probable that pilots would consider a control that builds up very slowly at first and then reaches its full rolling moment with a rush more objectionable than one which reaches its full value in the same time but at a more even rate of growth.

The lag and sluggishness are illustrated in the following sketch:



American tests[1, 2, 3] have demonstrated that both the lag and sluggishness may be finite though small and yet be unnoticed by the pilots. These tests were done on a Fairchild 22 aeroplane, a small aeroplane about 34 ft in span and with a top speed of about 130 m.p.h. and it was found for this aeroplane that, whilst a measured lag of 0·25 sec was definitely objectionable, a lag of 0·1 sec was unnoticed by the pilots. Similarly, a sluggishness of about 0·4 sec was objectionable, whilst a sluggishness of 0·1 sec was not.

The lag and sluggishness of a control are presumably determined by the manner and rate with which the circulation about the wing alters once the control is moved. It can be argued, on general grounds, that the lag and sluggishness will be proportional to c/V where c is the mean chord of the aeroplane and V is the forward speed (*cf.* Ref. 4), and hence the lag and sluggishness may be expected to decrease with increase of speed and to increase with increase of size of aeroplane. The values for the maximum amounts of lag and sluggishness that are unnoticed by a pilot are presumably determined, in the first place, by the speed of his reactions. It is conceivable that this speed may in some way be influenced by the speed and size of the aeroplane, but little is known about this; it will, therefore, be assumed that the maximum permissible lag and sluggishness are independent of the speed and size of the aeroplane and have the values suggested by the American experiments, namely, 0·1 sec. This suggests that it may be possible for the lateral controls of an aeroplane to be satisfactory at high speeds but unsatisfactory at low speeds, as far as promptness of response is concerned.

The requirements of even increase of response and of stick force with stick movement are obviously desirable in themselves, but in addition their satisfaction implies that no departure from standard technique is required of the pilot.

With regard to the requirement of adequate rolling action below the stall it is usually found that provided a rolling moment (c_l) of about 0·04 to 0·05 is available the control is adequate. The question arises, however, as to whether the use of high lift flaps will alter the minimum value of the available rolling moment required to give satisfactory control. The adequacy of a control is presumably judged in the main by the time taken to bank through a given angle, and this is determined by the rate of roll p. For a given aileron movement, the rate of roll quickly settles down to a constant value given by [5]

$$\frac{ps}{V} = -\frac{\lambda}{l_p} c_l \, ,$$

where l_p is the derivative of the rolling moment due to the rate of roll,

λ is a constant (average value about 0·8),

V is the forward speed,

and s is the wing semi-span.

Hence, for a given rolling moment, p is a minimum when V is a minimum, *i.e.* at landing. The tendency today is for landing speeds to remain constant or rise slightly; high lift devices are required only in so far as they permit of increased wing loadings. Since aeroplanes utilising high lift devices will not land at speeds lower than modern normal aeroplanes, it follows that they will not require a greater available rolling moment to give adequate control. In what follows it has been assumed, therefore, that the rolling action of a lateral control system is completely satisfactory if the available rolling moment coefficient up to the stall is never less than about $0 \cdot 05$.

The requirement of small but favourable yawing moments is not now considered to be as important as was at once thought. It would appear that whilst pilots like the yawing moments to be favourable, nevertheless, they rarely find any undue difficulty in coping with quite large adverse yawing moments particularly at small or moderate incidences. There is always the danger, however, that off a sharp stall the use of ailerons in an attempt to lift the falling wing may induce a spin if the yawing moments are appreciably adverse. It is worth noting that some American tests have demonstrated that the favourable yawing moments due to a spoiler control system are not subject to lag or sluggishness. It was found that a control which was normally objectionable on account of sluggishness was rendered passable when it was used on an aeroplane with some dihedral; the combination of dihedral and favourable yawing moment apparently results in an appreciable rolling moment in the required direction in a sufficiently short time to mask the worst effects of the sluggishness.

Some lateral control beyond the stall is another requirement to which at one time considerably more importance was attached than is the case today. Recent American experiments[1] have demonstrated that it is not in itself sufficient to ensure safe flying at low speeds; for some wing tip sections the changes in lift and flow pattern at the stall are violent and large and it may be expected that even with lateral control attempts at straight flight beyond the stall may yet result " in a series of violent oscillations during any of which considerable altitude may be lost or the direction of flight changed." It is probable, therefore, that the shape of the wing section used, particularly at the tip, will play an important part in determining the lateral stability and therefore the value of the lateral control beyond the stall.

3. *Lateral Control Devices for use with Full-Span Flaps.*—3.1. *Spoilers. General.*—The development of a satisfactory form of spoiler as a lateral control device for use with full-span flaps has received considerable attention in recent years. Two main types of spoilers have been developed, namely, the retractable-arc type and the hinged-flap type. The former type is in its simple form an arc which, when operated, moves more or less normally to the wing upper surface out of a slot in the wing. The hinged-flap type when not in use forms part of the wing upper surface and the hinge, about which it rotates, is generally on or near it; when in the " full up " position it may lie, like the retractable-arc spoiler, at an angle of 90 deg to the wing surface, although in many cases smaller angles such as 60 deg. are used. It will be seen that both types depend for their effectiveness on progressively spoiling the flow over the top surface and thus reducing the lift of the wing on which they are operating. The main difference between the two types lies in their possible hinge moment characteristics; the hinge moments of the retractable-arc type can theoretically be reduced to zero by making the arc circular and placing the hinge at the centre of curvature.

Unlike ordinary ailerons spoilers necessarily involve an overall loss of lift when in operation. Apart from the fact that this feature may demand some modification in handling technique it may prove a serious disadvantage in manoeuvres near the stall or ceiling.

Wind-tunnel measurements of the lag[7], yawing and rolling moments[8] of simple spoilers at various chordwise positions have been made in America and the main results are shown in Fig. 1. The spoilers tested were of the simple retractable-arc type but the results are a general indication of what may be expected with any simple type of spoiler. It will be noted that whilst the available rolling moments and favourable yawing moments generally increase with forward movement of the spoiler location there is a marked increase in lag. For the lag measurements the chord of the wing was 4 ft. and the tests were made at an incidence of 0 deg, when the air speed was 80 m.p.h., and an incidence of 15 deg, when the air speed was 40 m.p.h. The lag results are plotted again in Fig. 2 (a) on a non-dimensional basis by dividing the lag by c/V, and it will be seen that the two sets of results fall reasonably close to a mean curve. On this basis curves in Fig. 2 (b) have been drawn showing the most forward permissible position of a simple spoiler on wings of various chord lengths and for various minimum flying speeds, it being assumed that the maximum permissible lag is 0·1 sec. A typical F.A.A. high-lift aeroplane, for example, may have a landing speed of about 75 m.p.h. and a mean chord at the spoiler of about 7 ft; it will be seen that for such an aeroplane a location of the spoiler ahead of about $0\cdot75c$ would lead to excessive lag. An aeroplane would have to be unusually small and heavily loaded to permit of a location ahead of $0\cdot65c$. It will be seen, therefore, that in general a simple type of spoiler must be confined to the rear 30 per cent. of the wing where not only are the rolling moments comparatively small but decrease rapidly with increase in incidence. With most types of high-lift flaps it may be impossible to put spoilers so far back from the leading edge. On the other hand, there is some evidence that with very far forward spoilers there is a rapid decrease of rolling moment with decrease of incidence which is exaggerated by the presence of flaps[3]; the effect may be extreme enough to leave little or no control at the smallest incidences at which an aeroplane is flown, flaps down. Attempts therefore, have been made to develop spoilers having negligible lag which could be placed in the more favourable region lying between about $0\cdot3c$ and $0\cdot6c$ back from the leading edge. This development work has also concentrated on producing spoilers with satisfactory hinge moment and response characteristics.

3.11. Slot-lip ailerons (Fig. 3).—It was found that a slot through the wing behind the spoiler (whether retractable-arc or hinged-flap type) appreciably reduced the lag[3]. Various tests were made to discover the optimum slot size and shape using a hinged-flap type of spoiler, and arrangements of the slot-lip aileron (as this device was called) developed as a result of these tests, were tested in flight. These arrangements are shown in Fig. 3. The wind-tunnel tests showed these arrangements to have a lag less than 0·05 sec (lag $V/c < 0\cdot7$) and satisfactory hinge and rolling-moment coefficients, although the increment in the minimum profile drag coefficient due to them was in the order of 0·002 to 0·005.

In the first series of flight tests on a Fairchild 22 aeroplane, the slot-lip ailerons were tested at $0\cdot2c$ and $0\cdot45c$ back from the leading edge, the aileron size in each case being $0\cdot1c$ by $0\cdot5b/2$. These tests showed that, although the ailerons had no appreciable lag flaps up, they were unpleasantly sluggish in both positions. The sluggishness for the aileron in the $0\cdot2c$ position was appreciably worse than for the aileron in the $0\cdot45c$ position, and lowering the split-flaps appeared to introduce some lag with the aileron in the $0\cdot2c$ position and in both cases increased the sluggishness. Further tests revealed that the sluggishness of these ailerons at slow speeds was about 0·4 sec whilst ordinary ailerons in this aeroplane had a sluggishness of about 0·1 sec to which the pilots had no objection. The results of wind-tunnel measurements of the sluggishness of slot-lip ailerons at various chordwise positions are plotted in Fig. 4, where the results are shown non-dimensionally in terms of the time taken for the aeroplane to travel one chord length (c/V).* Accepting 0·1 sec as the maximum permissible sluggishness it would appear from this diagram that for minimum flying speeds of less than 90 m.p.h. and chord lengths of 5 ft or more it will generally be impossible to install slot-lip ailerons with a tolerable amount of sluggishness. The rolling moments developed by the slot-lip ailerons on the Fairchild 22 aeroplane were disappointing being only about two-thirds the rolling moments expected from the wind-tunnel tests; it was suggested, however, that the ailerons were not in fact deflected the full amount owing to structural flexure.

Later tests on a W.1.A aeroplane (*see* Fig. 3 (b)) with the aileron at $0\cdot3c$ showed much more satisfactory results. The sluggishness did not appear to be sufficient to be objectionable whilst

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* The American report[3] gives quite a large value for the sluggishness of a slot-lip aileron at $1\cdot0c$ which is indicated in Fig. 4. But it is difficult to see how a slot-lip aileron in this position should differ from an ordinary aileron and hence it should have a sluggishness which in general should be small enough to be objectionable.

the rolling moments were quite adequate. An analysis of the motion, however, indicated that the sluggishness of the controls was present but was largely masked by the prompt rolling action produced by the combination of the favourable yawing moments and the large dihedral. Lowering the flaps, which appear to be of the slotted Junkers type increased the rolling moments and slightly decreased the sluggishness.

Various modifications of the slot-lip aileron have also been tested; in one case, for instance, the aileron was formed out of the lip of the slot of a 26 per cent N.A.C.A. slotted flap[9] (*see* Fig. 3c). None of these modifications gave satisfactory results, the greatest difficulty being met with in developing satisfactory hinge moments.

These results give little promise of the early application of slot-lip ailerons. The extra drag involved is high, and the sluggishness is objectionable except perhaps on aeroplanes with large dihedral.

3.12. *Spoilers on the Courier* (*Fig.* 5).—Fig. 5 illustrates the type of hinged-flap being tested on the Courier. The spoiler is situated at $0 \cdot 5c$ behind the leading edge, its span being $0 \cdot 46b/2$ and chord about $0 \cdot 1c$. It will be seen that as the spoiler is brought into operation a gap is left between the spoiler and the wing surface which wind-tunnel tests have shown will reduce the lag to a negligible order. There is provision for testing two sizes of gaps and two stick gearings the usual parabolic gearing and a linear gearing. Tests were first made with the parabolic gearing and the ailerons were then found to give a very poor response for small movements of the stick about the neutral position. For large movements at high speeds the spoilers appeared to be too powerful and showed signs of overbalance. Tests were then made with the linear gearing but little improvement in the control characteristics resulted. The response for small movements was still poor, whilst for large movements the response was again sudden and dangerously powerful.

These controls as at present tested are therefore very unsatisfactory. The poor response for small movements may be partially due to sluggishness, which may well be a characteristic of all hinged-flap types of spoilers; on the other hand, it is possible that the gap as at present designed helps the flow round the spoiler so that the spoiler itself does not stall till it has been moved through a comparatively large angle. Further tests, therefore, are contemplated with modifications to the spoiler and gap to break up the flow through the gap.

3.13. *N.A.C.A. developments of retractable-arc spoilers* (*Figs.* 6, 7, 8).—Early flight tests of a simple circular-arc retractable spoiler situated $0 \cdot 2c$ back from the leading edge[1] on a rectangular wing showed, as noted above, a large and objectionable lag although the rolling control when fully developed was very powerful. Later a similar spoiler situated at $0 \cdot 765c$ back from the leading edge having a span of about $0 \cdot 48b/2$ and a height of about $0 \cdot 12c$ was tested on a rectangular wing equipped with full-span $0 \cdot 2c$ split flaps[2]. The lag with this spoiler was not noticeable to the pilots, although measurements showed it to be about $0 \cdot 1$ sec. The available rolling, moments were fairly powerful and were increased by about 12 per cent when the flaps were put down. The yawing action was not appreciable flaps up and was slightly negative flaps down. The pilots reacted favourably to these controls complaining only of the lack of feel and stick force.

More recently tests have been made of a circular-arc retractable spoiler on a wing with a 5 : 1 taper equipped with a full-span $0 \cdot 2c$ plain flap[10]. The spoiler was $0 \cdot 327\ b/2$ in span and $0 \cdot 105c$ in height and was situated $0 \cdot 735c$ back from the leading edge. Fig. 6 shows a sketch of the arrangement. The faces of the spoiler were formed by two curved plates touching at their lower edge and separated at their upper edges by a filler block giving the spoiler a flat top. The spoiler rotated about a hinge situated at the centre of curvature of the forward face. The rolling control was satisfactory at low incidences but was rather poor at high incidences. The lag, which was measured to be about $0 \cdot 1$ sec., was not objectionable to the pilots and the rate of increase of response with stick movement was considered satisfactory. Although the flat top of the spoilers was specifically introduced to provide " feel ", the stick forces were found to be very small and the feel was, therefore, inadequate. There is no report of unpleasant opening hinge-moments with these spoilers, although English tests of similar flat-topped spoilers have demonstrated that the suction over the top of the spoiler in the initial stages of its movement out of the slot produces " snatch " (*see* section 3.14).

Parallel with these flight tests a series of wind-tunnel experiments[11] have been made to develop retractable-arc spoilers with satisfactory lag, hinge moment and rolling moment characteristics. In these tests the spoilers moved in and out of slots running right through the wing and were operated with a large differential, the down-going spoiler partially emerging from the lower surface of the wing. After some preliminary tests with the slots slightly wider than the spoiler the slot width was increased to double the width of the spoiler and a plate or flap was fitted to the top of the spoiler and the bottom of the slot so as to close the slot when the spoiler was retracted. The effect of widening the slot was to reduce the lag and opening hinge moments and to increase the rolling moments. It was then found that, by venting the top and bottom of the spoiler and by tilting or hinging the upper flap, still further improvements in the hinge moment curve resulted. Two arrangements which were eventually developed and tested in conjunction with a full-span 26 per cent slotted-flap are shown in Figs. 7 and 8. The spoilers were $0{\cdot}375b/2$ in span and $0{\cdot}095c$ in height and were situated at about $0{\cdot}65c$ back from the leading edge. The measured hinge, rolling and yawing moments, flaps up and down, are shown in Figs. 7 and 8. The rolling moments available appear to be more than adequate whilst the very large increase in rolling moment when the flaps are lowered is noteworthy. For small initial movements of the spoilers, with flaps down, the response seems rather poor, however, and increases with an unpleasant rush at about 10 deg. spoiler movement. The hinge-moment curves call for further improvement, particularly with flaps down. It would appear that some further development work is required before these spoilers can be considered satisfactory.* It is understood that some flight tests are being considered.

3.14. *Retractable-arc spoilers on Falcon* (*Fig.* 9).—The spoilers tested on the Falcon are illustrated in Fig. 9. Initially they were made with flat tops of appreciable thickness as in the American tests referred to above (section 3.13) but the early flight tests demonstrated that the suction on the flat top produced an unpleasant snatch as the spoiler was moved from neutral. The spoilers, as finally tested, were simply curved metal plates, the shape of the curve being intermediate between the front and rear faces of the original spoilers. The spoilers were $0{\cdot}55b/2$ in span and about $0{\cdot}07c$ in height and were situated at a mean distance of about $0{\cdot}7c$ back from the leading edge. At low speeds the spoilers were found to be very heavy over the whole of their movement and the response, particularly over the first third of the stick movement, was poor and showed signs of being sluggish. This poorness of response for the initial stages of the stick movement persisted at all speeds although it was less marked at high speeds. For large movements, however, the response increased rapidly with speed, whilst the control lightened to the extent of feeling overbalanced, and there was some evidence of a tendency to flutter. With flaps down the behaviour was much the same as with flaps up, although the heaviness of the control was increased slightly.

It will be seen that in the form tested the controls were tricky and were safe only in the hands of a skilled and experienced pilot. It is believed that the unpleasant hinge characteristics of the spoilers are mainly due to large frictional and inertia forces that were involved in their operation and that the arcs of the spoilers were not truly circular. Modifications, therefore, are in hand to reduce the friction and inertia of the system and to reshape the spoilers to true circular arcs with the hinge at the centre of curvature. The modified spoilers will lack feel but it is believed that this is probably best supplied artificially, *e.g.* by a spring. The response over the initial stages of the movement may be improved by altering the stick gearing, but if the control is seriously sluggish it may be very difficult to cure satisfactorily.

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* Since this report was written Blackburn Aircraft Limited have investigated similar plug-type spoilers but with the top bevelled to various angles[34]. The bevel was found to have a profound effect on the hinge moments, and it is suggested that if the bevel angle is arranged to vary with spoiler setting something approaching a linear hinge-moment variation should result. The mechanical complications of such an arrangement are, however, very serious.

3.15. *Blackburn retractable-arc spoilers to be tested on the high-lift Lysander* (Fig. 10).—The retractable-arc spoilers developed by Messrs. Blackburn[12] are illustrated in Fig. 10. They are $0 \cdot 27b/2$ in span and $0 \cdot 094c$ in height and are situated at about $0 \cdot 57c$ behind the leading edge. They have so far only been tested in the wind-tunnel in conjunction wth a 50 per cent Blackburn flap, as a preliminary to proposed flight tests on a Lysander fitted with high-lift flaps and slats. In the initial tests the spoiler was very similar to the first American flat-topped spoiler but, as in the tests on the Falcon spoiler, they were found to be unsatisfactory owing to the large opening moments involved. It was found, however, that by venting the top of the spoiler, as shown in the figure, the hinge-moment characteristics were apparently rendered satisfactory. The measured hinge and rolling moments, flaps up and down, are shown in Fig. 10. There were no measurements made between 0 deg and 20 deg aileron movement, and hence it is not certain that unpleasant kinks in the hinge-moment curves do not exist in that region. However, if we accept the smooth curves shown, it appears, comparing these curves with those of Figs. 7 and 8, that from the point of view of the hinge and rolling-moment characteristics the simple vent through the top of the spoiler is more satisfactory than the elaborate arrangements developed by the Americans. If it fulfils the promise of the wind-tunnel tests and does not suffer seriously from lag or sluggishness, the Blackburn arrangement should prove an excellent control with high-lift flaps.

3.16. *Tandem retractable-arc spoilers* (*Fig.* 11*c*).—Some results obtained by the Americans in wind-tunnel tests of simple retractable-arc spoilers in tandem are worth noting. The arrangement tested is illustrated in Fig. 11 (c). The spoilers were each $0 \cdot 375b/2$ in span and $0 \cdot 1c$ in height and were situated at $0 \cdot 3c$ and $0 \cdot 83c$ behind the leading edge. It was found that this combination had the same negligible lag in action as the rear spoiler, whilst the rolling moments produced were the same in magnitude and character as those produced by the front spoiler alone. The combination therefore retained the most desirable characteristics of the individual spoilers. With the spoilers staggered spanwise relative to each other, the rolling moments increased a little, but the lag characteristics at high incidences appreciably deteriorated. No attempt appears to have been made to explore further into the potentialities of this arrangement. It will be noted, however, that with such an arrangement there is always the disadvantage that it is frequently impossible to fit a far-back rear spoiler in with most high-lift large-chord flaps. In addition, the control mechanism will necessarily become complicated.

3.2. *Other Devices for use with Full-Span Flaps.*—In addition to spoilers the Americans have tested a number of other devices which suggest themselves as possible forms of lateral control for use with full-span flaps. These include

(i) controllable front auxiliary aerofoils[2],
(ii) external ailerons[2],
(iii) upper surface ailerons[2],
(iv) narrow chord ailerons working behind Zap type flaps[2],
(v) narrow chord ailerons formed from rear part of N.A.C.A. 26 per cent slotted flap[9].

These devices are illustrated in Fig. 12.

3.21. *Controllable front auxiliary aerofoils* (*Fig.* 12*a*).—The controllable auxiliary aerofoils[2] tested each covered the wing semi-span and were $0 \cdot 15c$ in chord. In the neutral position the chords were parallel to the wing chord and with stick movement one aileron rotated downwards to a maximum angle of 45 deg whilst the other remained stationary. Preliminary wind-tunnel tests demonstrated that as a control device the auxiliary aerofoils were very unsatisfactory, there was a considerable lag in their action whilst the stick forces appeared to be excessive. No further attempts at development were made, therefore.

3.22. *External ailerons*[2] (*Fig.* 12*b*).—The external ailerons tested were $0 \cdot 55b/2$ in span and $0 \cdot 15c$ in chord. They could be operated either up or down to a maximum angle of 45 deg but only one aileron was moved at a time. It was found that the downward movement resulted in a large lag in response but with the upward movement the lag was negligible. The rolling action was weak and approximately constant at all speeds but was not proportional to stick deflection, being very slight over the first half of the movement. The stick-force characteristics were generally unsatisfactory, the force was heavy and varied with stick deflection in an irregular manner. Shifting the hinge axis backwards reduced the magnitude of the stick force but its irregular variation with stick movement was unaffected, with the result that, whilst over some parts of the movement the force was still fairly heavy, over other parts the ailerons were on the point of overbalance. The yawing action was favourable and there was an appreciable amount of control beyond the stall.

It would appear from these tests that without a great deal of further development work being done, the prospects of obtaining a satisfactory control by means of external ailerons are very remote.

3.23. *Upper surface ailerons*[2] (*Fig.* 12*c*).—The upper surface ailerons were $0 \cdot 55b/2$ in span and $0 \cdot 182c$ in chord, they operated upwards to a maximum angle of 40 deg. The rolling-moment characteristics were satisfactory, as in this respect these ailerons appeared to behave much the same as ordinary ailerons. The stick forces were, however, unusually heavy and the yawing action was adverse.

The heavy stick forces are a drawback to this form of control but it is conceivable that a satisfactory degree of balance may be obtained by using a double-hinged flap as described in Ref. 30. Some attempts to balance the aileron by providing it with a slot and a setback hinge are described in Ref. 31, but the results were never very satisfactory. The restriction of the flap to the split type is not a serious disadvantage provided only a simple flap is contemplated. From the point of view of the lift produced the split-flap is barely inferior to the slotted-flap but it involves more drag[13]. The more ambitious forms of high-lift flaps, however, all require slotted-flaps and could not be combined with upper surface ailerons. A possible exception perhaps is the Fowler flap, but the upper surface aileron would then leave little room for the operating mechanism of the flap.

Upper surface ailerons, like spoilers, act by reducing the overall lift, a feature which may, as already remarked, prove objectionable.

3.24. *Narrow chord ailerons behind Zap-type flaps*[2] (*Fig.* 12*d*).—The narrow chord ailerons were $0 \cdot 83b/2$ in span and $0 \cdot 136c$ in chord whilst the flap span was $0 \cdot 789b$ and flap chord was $0 \cdot 2c$. The aileron movement ranged between 25 deg up and 14 deg down whilst the flap could be lowered to 60 deg retracting forward and upwards in a manner similar to a Zap flap.

These controls were very favourably reported on; the available rolling moments were somewhat greater than those of standard ailerons and the general characteristics including the stick forces were very satisfactory with the flaps up or down. The rolling moment was reduced very little by putting the flaps down. The downward movement probably contributes much less to the rolling moment with the flaps down than up, but the rolling moment due to the upward moving aileron is probably increased (*cf.* upper surface ailerons[31]). The yawing action was adverse but small and there was little control beyond the stall. It would appear that where the use of a split or Zap type of flap is contemplated, this type of control is well worth consideration.

A similar arrangement that has been tested both in flight and in the wind-tunnel is a combination of a Zap flap and Zap aileron[14] (*see* Fig. 12*e*) on a Fairchild 22 aeroplane. The flap was $0 \cdot 3c$ in chord and in the fully extended position the leading edge of the flap was at $0 \cdot 8c$ behind the leading edge of the wing. The span of the flap was $0 \cdot 83b/2$ and the maximum angle to which it was set down was 59 deg. Two sets of ailerons were tested, one set was $0 \cdot 5b/2$ in span and $0 \cdot 18c$ in chord, the other was $0 \cdot 46b/2$ in span and $0 \cdot 22c$ in chord. Both sets were fitted with leading edge slats $0 \cdot 115c$ in chord. The aileron movement ranged from 30 deg up to 15 deg down. The wind-tunnel tests demonstrated that the ailerons and their supports increased the drag at low incidences by about 15 per cent and in general caused a slight decrease in the lift. In flight both sets of ailerons were found to be about equally effective and were considerably more effective than standard ailerons. However, the stick-force characteristics were unsatisfactory for both sets of ailerons, the forces were large at the high speeds and very small at the low speeds whilst the variation of stick force with deflection was irregular. The poor stick-force characteristics and the large amount of extra drag involved both constitute serious drawbacks to this form of control.

3.25. *Plain ailerons behind a full-span slotted-flap*[9] (*Fig.* 12*f*).—Plain ailerons behind a full-span N.A.C.A. 26 per cent slotted-flap have been tested in the N.A.C.A. 7 by 10 ft wind-tunnel, The chord of the ailerons was $0 \cdot 1c$ and the span was $b/2$. The results for the yawing, rolling and hinge-moment coefficients estimated for two-dimensional lift and drag measurements are shown in Fig. 13. It will be seen that with the flaps up, as might be expected, the general characteristics were very satisfactory. As the flaps were lowered beyond about 30 deg, however, the characteristics rapidly deteriorated. The response for small movements then became progressively poorer and the available rolling moments for both up or down aileron movement decreased in addition the hinge and adverse yawing moments increased rapidly. From these results it is doubtful whether even a passable control could be obtained with these ailerons for a flap setting greater than 30 deg; this would imply an appreciable sacrifice (about 15 per cent) of the lift increment due to the flaps. The large negative hinge moments when the flaps are set down would make it very difficult to avoid overbalance if any degree of upward differential were employed. It is conceivable that by increasing the chord of the ailerons the deterioration in the response characteristics for small movements as the flaps are lowered might be appreciably reduced, although the balance problem may become more serious.

4. *Lateral Control with Nearly-Full-Span Flaps*.—4.1. *General*.—There are a number of lateral-control devices which require a small part of the wing span to the exclusion of the flap, and hence they can only be used in conjunction with nearly-full-span flaps. When compared with devices that permit of the use of full-span flaps they therefore suffer from the disadvantage that they entail some reduction in the lift increment due to the flap. Hence, before considering these devices in detail it is desirable to examine the existing data on the loss of lift involved in restricting the span of the flap.

Some experimental results for plain[15], split[16 17] and slotted[18] flaps of the ratio of the lift increment obtained with part-span flaps ($\triangle C_{Lp}$) to the lift increment obtained with full-span flaps ($\triangle C_{Lf}$) on wings of various taper ratios are shown in Figs. 14a, b and c. The corresponding theoretical results[19] for plain-flaps are shown in Fig. 14d. It will be seen, as might be expected, that for centre-section flaps the fractional loss of lift increment is rather less than the fractional span of the wing which is unflapped and decreases with wing taper ratio. In Fig. 15 the theoretical and experimental values for the fractional loss of lift increment with flaps $0 \cdot 75b/2$ in span are plotted against wing-taper ratio, and in addition a curve is drawn showing the corresponding ratio of the wing area which is unflapped. It would appear from the sparse experimental data that the fractional losses for the plain and slotted-flaps are both roughly proportional to the fractional unflapped wing area, but the corresponding loss for the split-flaps and the loss derived theoretically decrease more slowly than the fractional unflapped wing area with increase in taper ratio. Accepting a taper ratio of 2 : 1 as fairly representative of modern aeroplanes, it will be seen that with $0 \cdot 75b/2$ span flaps a loss of the lift increment due to full span flaps in the order of 15 per cent may be expected. It is believed that this loss is the largest sacrifice tolerable for aeroplanes designed to meet modern high-lift requirements and can only be justified if the lateral-control system involved is very satisfactory. It is suggested, therefore, that in considering lateral-control devices requiring part of the span of a moderately tapered wing only those devices requiring at the most about $0 \cdot 25$ of the span can be entertained. With highly tapered wings this restriction can be to some extent relaxed.

As against the loss in lift increment involved in the use of part-span flaps it is worth noting that model experiments[20] have indicated that there is a serious deterioration in lateral stability near and at the stall flaps down when the flaps cover the whole of the wing span. Only one recorded case of such deterioration with full-span flaps has been noted in flight[32], but in general the few full-span flaps that have been tested in flight have been comparatively small in chord and unambitious. With the use of large-chord high-lift flaps that are anticipated in the near future it is possible that appreciable deterioration in lateral stability near the stall may occur if the flaps are made to cover the whole wing span. In such a case the greatest lift of the wing and flaps that can safely be used may fall appreciably short of the actual maximum and this loss of available lift may well be of the same order as the lift lost by using nearly full-span flaps.

4.2. *Short-Span, Wide-Chord Ailerons* (*Fig.* 16).—4.21. *Hinge parallel to the wing span.*—Short-span wide-chord ailerons immediately suggest themselves for use with nearly-full-span flaps. Some flight and wind-tunnel tests[1,6] have been made in America on plain ailerons of span about $0 \cdot 3b/2$ and chord about $0 \cdot 4c$. These ailerons are a little wider in span than the maximum permissible width suggested above, nevertheless the results give an indication of what may be expected with short span ailerons. The results of some wind-tunnel tests of these ailerons on a rectangular wing are shown in Fig. 16a. It will be seen that the rolling moment available is more than adequate and for upward movements of the aileron favourable yawing moments over a large part of the incidence range can be obtained. The results also suggest that these ailerons retain their rolling power at higher incidences than the normal ailerons. Very similar results were obtained on wings with rounded tips[21].

The flight tests confirmed that adequate rolling moments were available although the promise of appreciable control at high angles of incidence was not fulfilled. The stick forces were rather large but the ailerons were unbalanced. The behaviour of the ailerons in a sideslip was found to be unsatisfactory, to quote the American report[1], " the forward aileron tended to trail up sufficiently to overbalance the inherent banking effect of the wings, so that a fairly heavy force had to be applied to the stick to hold the aileron down and to prevent the wing from ' digging in ' ". It is difficult, without further evidence, to account satisfactorily for this tendency for the ailerons to overbalance in a sideslip, but a possible explanation is that the root section of the rear wing was shielded by the fuselage in the sideslip and consequently suffered a local loss of lift which, like the loss of lift due to a negative centre section flap, increased the downwash at the rear wing aileron. To the pilot this had the same effect as an increase in upwash at the forward aileron. Because of the large value of b_1 for these unbalanced wide-chord ailerons, this increase of downwash at the outer aileron was apparently sufficient to overbalance the control.

If this explanation is correct then it appears that any method of balancing these controls that does not involve an appreciable reduction in b_1 will not affect this tendency to overbalance in a sideslip although it will reduce the stick forces involved. Balance by means of a geared tab or by means of differential and a fixed tab[33] may not therefore be completely satisfactory, and it is probable that the most satisfactory form of balance would be obtained by means of a set-back hinge coupled with nose shrouds.

Short span ailerons[22] have also been tested in the 24-ft tunnel at the Royal Aircraft Establishment on a Fleet Air Arm high-lift model (Fig. 16b). These ailerons were $0 \cdot 25b/2$ in span and $0 \cdot 5c$ in chord and the design was based on an early type of Blackburn slotted-flap with a sharp leading edge. They were arranged to operate over a range of + 30 to − 15 deg with the flap neutral; with the flap lowered both ailerons operated from a neutral position of + 30 deg over the range 0 to + 45 deg. The rolling moments obtained, flaps up and down, slats closed, are shown in Fig. 16b; it will be seen that the rolling control available was adequate in both cases although with flaps up the upward-moving aileron was relatively inefficient. It is suggested that this loss in efficiency was due to the sharp nose of the aileron and could probably be avoided by rounding the nose. With the slats open the ailerons were found to be as effective over the required incidence range as with the slats closed. It is worth noting that the down rigging of the ailerons gave a lift coefficient increment of about $0 \cdot 19$ or about 10 per cent of the increment due to the flaps.

4.22. *Short-span, skew-hinge ailerons.*—It has been suggested that a short-span aileron with a skew-hinge might be more effective than one with the normal spanwise hinge. Wind-tunnel tests have been made in America of skew-hinge ailerons on rectangular wings with straight and rounded tips[23,21] (*see* Fig. 16c); the maximum angle of skew tested was, however, only 20 deg. On the rectangular wing with straight tips the skew-hinge ailerons were found to give much the same results as the normal-hinge ailerons at moderate angles of incidence, but were slightly inferior at high angles of incidence. On the wing with rounded tips, however, the skew-hinge ailerons were on the whole slightly superior to the normal-hinge ailerons. In general there would appear to be little to choose between the two types of aileron.

It has been pointed out that skew-hinge ailerons may appear to maximum advantage when the inboard end of the aileron hinge begins at the trailing edge of the wing and the angle of the hinge is of the order of 45 deg (*see* Fig. 16d). There would then be no break between the aileron and the wing when the aileron is operated. Reports have been received that ailerons of this type have been tested on a Messier aeroplane in France and were found to be very satisfactory. It is proposed to investigate the possibilities of these ailerons at the Royal Aircraft Establishment. It must be noted, however, that with the aileron span limited to 0·25 wing semi-span, as suggested above, the area of these ailerons are necessarily severely restricted and may not be enough to give adequate rolling control. Thus, with a wing of 6: 1 aspect ratio the maximum aileron area possible is about 0·09 of the wing area; this area is usually more than sufficient for normal small-chord ailerons but it is very doubtful whether it is sufficient for small-span ailerons situated at the wing tip.

4.23. *Combination of spoilers and short-span ailerons* (*Figs.* 11*a* and *b*.).—Where the rolling action of short-span ailerons may prove inadequate at high incidences, particularly if more severe span restrictions are imposed than has been considered above, it has been suggested that, in addition, a small forward spoiler might profitably be used. The action of the aileron might be expected to mask to some extent the lag of the spoiler.

Some arrangements that have been tested in flight[1] and in the wind-tunnel[24], in America, are shown in Figs. 11*a* and *b*. In the wind-tunnel tests the short-span ailerons were $0 \cdot 3b/2$ in span and $0 \cdot 4c$ in chord. The spoiler tested was of the flap-hinge type. Various spoiler locations were tested and it was found that to avoid some reduction in the joint rolling action due to interference between the spoiler and aileron, the spoiler had to be placed inboard of the aileron, leaving a gap about $0 \cdot 2b/2$ between the spoiler and aileron. The spoiler was $0 \cdot 15c$ in chord, $0 \cdot 1b/2$ in span and rotated about a rear hinge situated at $0 \cdot 2c$ back from the leading edge. The rear hinge was chosen with the object of investigating the possibilities of balancing the hinge moments of the aileron against those of the spoiler by interconnecting the two. The rolling moments of the combination were found, as expected, to be appreciably greater than those due to the aileron alone, particularly at high angles of incidence where the increase of rolling moment coefficient due to the spoilers was of the order of 0·02 (*cf.* Figs. 16a and 11a). The spoilers also introduced some control beyond the stall, and the yawing moments were made more favourable. The measured hinge moments were appreciably reduced by coupling the spoilers and ailerons and in general these tests gave great promise that any degree of balance could be obtained by a suitable choice of the sizes, locations and linkages of the spoiler and aileron.

The flight tests were first made with a rear hinge spoiler $0 \cdot 15b/2$ in span and $0 \cdot 15c$ in chord coupled with an aileron $0 \cdot 33b/2$ in span and $0 \cdot 35c$ in chord (Fig. 11b). The spoiler only came into action after the ailerons had been deflected 5 deg and it was found that when the stick was moved sufficiently to move the spoiler the control force changed sign after the roll had started. This overbalance was not shown by the wind-tunnel tests and was probably due to the decrease of the hinge moments of the ailerons with rotation of the wings[5] whilst the hinge moments of the spoilers were unaffected by the rotation. The increase in rate of roll as the spoilers came into action was unpleasantly sudden and marked. The yawing action was small but favourable and there was appreciable control beyond the stall. Attempts to produce more satisfactory stick-force characteristics by reducing the spoiler movement and area were only partially successful.

A retractable circular-arc spoiler $0 \cdot 435b/2$ in span and $0 \cdot 087c$ in height was next tested in conjunction with the short-span ailerons (Fig. 11b). Here, the spoiler hinge-moments were negligible and the aileron hinge-moments were, therefore, unaffected. The combined action of these two controls was quite satisfactory; a slight increase in the rate of roll was noticeable as the spoiler became effective but it was not objectionable. The yawing action was favourable and there was appreciable control beyond the stall. No attempt was made to reduce the lag of the spoilers by venting, etc., nevertheless the lag was not obtrusive being largely masked by the immediate action of the ailerons. The lag may, in fact, have been appreciably reduced; as noted in section 3.16 tests of combinations of spoilers in tandem have shown that the lag of the combination is much the same as that of the rear spoiler alone, and the aileron may be regarded in this connection as a rear spoiler.

These tests demonstrate that the use of a small spoiler to augment a lateral-control system which may be otherwise inadequate at high incidences has considerable possibilities, and further investigation would be well justified.

4.3. *Floating-Tip Ailerons.*—Floating-tip ailerons are ailerons which are situated at the wing tips but which are not an integral part of the wing. They are generally hinged at about 15 per cent. of their chord back from their leading edge and are rotated relative to their floating angle which they take up in the neutral position. They have been tested in the wind-tunnel[25, 26] and in flight, in America. The results of some of the wind-tunnel tests of full-chord, short-span, floating-tip ailerons on a rectangular wing and on a wing of 5 : 3 taper ratio are reproduced in Fig. 17. It will be seen that the rolling moments are more than adequate in both cases and were still very appreciable at an incidence of 40 deg. The yawing moments were generally favourable and small. Varying the hinge position did not affect the rolling moments much, but it was found that flutter was liable to occur, particularly at high incidences for large deflections, if the hinge position was set much further back at $0 \cdot 15c$.

The floating-tip ailerons tested in flight are shown in Fig. 17c. These ailerons were found to be about half as effective as conventional ailerons at normal incidences but some control was retained beyond the stall. Apart from the poor rolling action the general characteristics of these ailerons were favourably reported on by the pilots; the yawing action was small but favourable, and the variations of response and stick force were both nearly linear with stick deflection. The comparatively poor rolling action of these ailerons is not surprising in view of their relatively small area which was about $0 \cdot 09$ wing area. As already remarked, for ailerons concentrated at the wing tips a larger area than usual is required to compensate for the spanwise drop in lift towards the wing tips. The wind-tunnel tests indicate that for floating-tip ailerons the area should be about $0 \cdot 15$ wing-area, *i.e.* nearly twice the area actually used in flight.

These results suggest that on the whole a fairly satisfactory control may be obtained with floating-tip ailerons. It has been suggested that they would have the advantage that the normal demands on the torsional stiffness of the wing could be considerably reduced by hinging the ailerons on the flexural axis. The flexural axis is generally in the region of $0 \cdot 25c$ to $0 \cdot 3c$ and the hinge cannot be set back further than the centre of pressure (about $0 \cdot 25c$); and in any case to avoid flutter of the type met with in the wind-tunnel tests it may not be possible to hinge the ailerons further back than $0 \cdot 15c$ without seriously restricting the aileron movement. A serious disadvantage, from the high lift point of view is the large loss of possible lift involved (about 10 per cent. if the area is 15 per cent. of the wing area) since the ailerons can carry little of the lift usually borne by fixed wing tips. By fitting the ailerons with flaps rigged upwards their floating angle can be raised and some of the lift regained, but the tests showed that the flutter problem then becomes more acute whilst, as might be expected, the yawing moments tend to become adverse.

Wing-tip ailerons that do not float may perhaps merit some consideration. They would presumably require much the same area as floating-tip ailerons, *i.e.* about $0 \cdot 15$ wing-area, but would not reduce the available lift as much as floating-tip ailerons. They would of course give little or no control beyond the stall and may involve large adverse yawing moments particularly at high angles of incidence.

4.4. *The Use of Part of Rear Flap of Large N.A.C.A. Double-Slotted Flap as Aileron.*—The N.A.C.A. have recently completed a series of tests of a large double-slotted flap[28] the components of which were 0·4*c* and 0·26*c* in chord. A summary and analysis of these tests will be found in Reference 29. The results showed that there was little serious falling off in the lift increment due to the second flap as the main flap was lowered. This suggests that the use of part of the second flap as an aileron should result in a rolling control that is fairly consistent, at least as far as downward movements of the ailerons are concerned, over the whole incidence range, flaps up or down. Rough calculations have been made of the rolling moments available for a wing of 5 : 3 taper and 6 : 1 aspect ratio, having a double-slotted flap and various portions of the rear flap as ailerons operating over the range + 25 to − 15 deg. from various neutral positions rigged down relative to the first flap. The corresponding maximum lift coefficients of the wing have also been calculated. The results, flaps up and down, are shown in Figs. 18 and 19, respectively, for the two wing sections NACA 23012 and NACA 23021. For flaps down the results are only given for an incidence $\alpha = \alpha_0 + 20$ deg. which corresponds practically to the incidence at maximum lift. It will be seen that with flaps up any aileron span greater than about 0·25 wing semi-span will give adequate rolling moments (*i.e.* $c_l > 0\cdot05$) over the whole incidence range. With the flaps down the calculations suggest that an aileron span of upwards of about 0·25 wing semi-span is necessary depending on the neutral angle down to which the ailerons are rigged. Considering the lift coefficients that result in each case, however, it appears that, of all the possible arrangements giving an available c_l of 0·05, ailerons of span about 0·45 wing semi-span set down about 15 deg. will result in the least loss of maximum lift. For such ailerons the loss in $C_{L\,\text{max.}}$ is about 0·1 or about 3 per cent. of the $C_{L\,\text{max.}}$ possible with full-span flaps. It is interesting to note that even if the whole of the second flap is used as an aileron rigged down 15 deg. the rolling moments available are more than adequate, whilst the loss in $C_{L\,\text{max.}}$ is only 0·3 or 9 per cent. Further downrigging beyond 15 deg. would, of course, reduce this loss in $C_{L\,\text{max.}}$ but it is anticipated that the response for small movements of the ailerons from neutral would then deteriorate rapidly and the control as a whole would consequently suffer.

For these calculations it has been assumed that the response for upward movements of the ailerons beyond a setting of 0 deg. relative to the main flap would not be seriously affected by the main flap position. But in the case of a plain aileron behind a 26 per cent. slotted flap[2] referred to above (*see* section 3.25 and Fig. 13) the response for upward movements did in fact deteriorate rapidly for flap settings greater than about 30 deg. although the flap could not be considered fully down till it had reached a setting of about 40 deg. However, in the case of the large double slotted flap it is to be hoped that the considerably larger chord of the aileron will help to preserve the response for upward movements till the flaps are fully down; in any case this part of the aileron movement contributes only a small part to the rolling moments calculated.

It would appear then that the advantage of this type of control over the short-span, wide-chord aileron or floating wing-tip aileron is its promise of adequate control with a smaller sacrifice of lift. There are, however, disadvantages which cannot be left out of consideration. It is known that the efficiency of slotted ailerons like that of slotted flaps is generally very sensitive to the accuracy with which the slot is made and the degree of distortion which the aileron will undergo when in operation. Slotted ailerons, therefore, demand a high degree of skill and workmanship in their construction. Further, the flaps follow paths which require either a track or link mechanism. With such a mechanism, designers will probably have considerable difficulty in devising a method of operation of the aileron that will fulfil the requirements of even increase of response of stick force with stick deflection and will ensure a satisfactory degree of balance over the whole speed range. The difficulties of balance will be aggravated by an increase in heaviness and large negative hinge moments for neutral settings that will probably occur as the flaps are set down (*cf.* section 3.25). The adverse yawing moments may also become large and troublesome with the flaps down. Nevertheless this method of control is sufficiently promising to merit further investigation.

5. *General Conclusions.*—A brief summary of the main characteristics of the various lateral control devices described above is given in convenient form in Tables 1A and B.

It appears from the foregoing that, of the devices that can be used with full-span flaps the most promising are spoilers and ailerons behind Zap-type flaps. Of spoilers it can be said that whilst none has yet been developed that can safely be applied to any but experimental aircraft, nevertheless, there is a reasonable chance that a spoiler can be developed that will be a passable control if not possessing all the desirable features of the best standard ailerons. The available rolling moments are adequate, whilst it appears to be a simple matter to reduce the lag to negligible proportions; the problems that remain are the development of satisfactory hinge-moment characteristics and possibly the reduction of sluggishness. Satisfactory hinge-moment characteristics can, in the last resort, be obtained by using circular-arc spoilers with an artificial feel introduced, say, by means of a spring. With a simple spring, such an arrangement would show no change of stick force with speed, a feature which is not a serious disadvantage but is nevertheless unattractive. The installation of a spring, which would " harden up " at any required rate with speed, should not, however, prove unduly difficult. The problem of sluggishness may be more difficult to solve satisfactorily; pushing the spoiler location back is only a partial solution and introduces other problems.

The characteristics of the ailerons behind the Zap-type flap are sufficiently good to make them well worth consideration where this type of flap can be reasonably entertained. As already remarked, however, the more ambitious types of high-lift devices generally involve large-chord, slotted flaps which cannot be combined with this method of control. An interesting compromise which has been suggested is the use of a high-lift flap over about 60 per cent. of the span, say, with $0 \cdot 2c$ to $0 \cdot 25c$ chord ailerons behind $0 \cdot 3c$ chord Zap-type flaps over the remaining 40 per cent. of the span. This arrangement will give less lift than with the high-lift flaps covering the whole span, but the lift sacrificed may be worth the good lateral control obtained. For example, if the high-lift flaps employed are $0 \cdot 4c$ Fowler flaps (for which $\triangle C_L = 2 \cdot 0$) the increment in lift coefficient sacrificed will be about $0 \cdot 2$.

However, if a designer is prepared for some sacrifice of lift all the devices considered above for use with part-span flaps merit consideration. Of these devices we have most information about short-span ailerons. They have the same general characteristics as normal ailerons and should provide adequate control if the span is not limited to less than about 25 per cent. of the wing semi-span. Their balancing should not be difficult, and they should permit of a certain amount of downrigging which will help to recover some of the lift lost. Downrigging, however, may in general require the ailerons to be of slotted design and may complicate the control mechanism. The greater inertia of wide-chord ailerons as compared with normal ailerons may prove to be their most unpleasant feature. Tests so far made do not indicate any marked advantage to be gained by making the hinges skew, but this is a matter for further investigation.

Where a more severe restriction on span is contemplated than is suggested above the combination of a short-span aileron with a small forward spoiler may prove a satisfactory control although the control mechanism will be somewhat complicated.

Floating wing-tip ailerons give promise of very satisfactory control characteristics, probably better than those of short-span ailerons. However, their use involves the sacrifice of most of the lift that would normally be borne by fixed wing tips, but since they need only cover about 15 per cent. of the wing area to give adequate control, the lift sacrificed is about 10 per cent. of the total lift, a sacrifice which may in some cases be acceptable. They have the additional advantage that if they can be hinged on the flexural axis the demands on the torsional stiffness of the wing are decreased, thus permitting some reduction in structure weight.

The use of part of the rear flap of a large double-slotted flap as an aileron is attractive in so far as it promises adequate control, flaps down, with a maximum lift coefficient that need only be about 3 per cent less than that obtained with full span flaps without ailerons. Further investigation is necessary, however, into the hinge moment, yawing moment and response characteristics with flaps down; there is reason to believe that it may be difficult to make these characteristics satisfactory. The complication of the control mechanism necessary may be found to be prohibitive.

To sum up, it appears that no satisfactory method of lateral control has yet been developed that permits of the full use of high-lift devices covering the complete wing span. For the present, therefore, designers must accept a lateral control which restricts to some extent the span or type of flap; the maximum lift will, therefore, fall short of the maximum possible with full-span flaps. A number of such methods of lateral control which are fairly satisfactory are available. These methods each have their good and bad points; whether one method is more suitable than another will depend to a large extent on the particular aeroplane for which they are being considered. It is hoped that the foregoing summary will be of some help to the designer in making the choice.

TABLE 1A

Summary of Main Characteristics of Some Lateral Control Devices for Use with Full Span Flaps

Type of control	Figs.	Probable dimensions required	Remarks		Refs.
			For	Against	
1. Retractable-arc spoilers.	1, 2, 6, 7, 8, 9, 10	$0 \cdot 4b/2 \times 0 \cdot 1c$	(*a*) Favourable yawing action. (*b*) Some control beyond the stall. (*c*) Wing stresses set up at high speeds less serious than with ordinary ailerons. (*d*) Effectiveness generally increased by flaps.	(*a*) Lift is lost when spoiler operates. (*b*) In rear positions, effectiveness is rapidly lost with increase in incidence. (*c*) In forward positions, modifications are necessary to reduce lag and sluggishness. (*d*) Difficulty has been experienced in obtaining satisfactory hinge moments.	1, 2, 8, 9, 10, 11, 12, 24.
2. Hinged-flap spoilers.	5	$0 \cdot 4b/2 \times 0 \cdot 1c$	(*a*), (*b*) and (*c*) as above.	(*a*), (*b*), (*c*) and (*d*) as above. (*e*) The response for initial movements is generally poor.	1, 24
3. Slot-lip ailerons.	3, 4	$0 \cdot 5b/2 \times 0 \cdot 1c$	(*a*), (*b*) and (*c*) as above.	(*a*), (*b*) as above. (*c*) Sluggish even as far back as $0 \cdot 45c$.	3, 7, 9
4. Tandem retractable-arc spoilers.	11*c*	$0 \cdot 4b/2 \times 0 \cdot 1c$ (one well forward and one well back).	(*a*), (*b*) and (*c*) as above. (*d*) No serious decrease in rolling action with incidence. (*e*) Negligible lag.	(*a*) as above. (*b*) Difficult to fit rear spoiler in with large chord slotted flaps. (*c*) Control system is complicated.	7

TABLE 1A (*Contd.*)

Type of control	Figs.	Probable dimensions required	Remarks		Refs.
			For	Against	
5. Controllable front auxiliary aerofoils.	12A	$b/2 \times 0{\cdot}15c$	—	(*a*) Large lag, (*b*) Excessive stick force.	2
6. External ailerons.	12*b*	More than— $0{\cdot}55b/2 \times 0{\cdot}15c$	(*a*) and (*b*) as for spoilers.	(*a*) Weak rolling action, considering area of control. (*b*) Poor response for initial movements. (*c*) Hinge moments large and vary irregularly with aileron movement.	2
7. Upper surface ailerons.	12*c*	$0{\cdot}15b/2 \times 0{\cdot}2c$	(*a*) Response and rolling-moment characteristics similar to those of standard ailerons.	(*a*) Lift is lost when aileron operates. (*b*) Large hinge moments difficult to balance. (*c*) Restricts flap to split or possibly Fowler type.	2
8. Ailerons behind Zap-type flap.	12*d*	$0{\cdot}5b/2 \times 0{\cdot}15c$ or $0{\cdot}4b/2 \times 0{\cdot}25c$	(*a*) Response and rolling-moment characteristics very good. (*b*) Hinge moments light, flaps up or down, and vary linearly with stick movement.	(*a*) Small adverse yawing action. (*b*) Restricts flap to split or Zap-type of flap.	2
9. Zap ailerons and Zap flap.	12*e*	$0{\cdot}5b/2 \times 0{\cdot}2c$	(*a*) as above.	(*a*) Increases minimum drag appreciably. (*b*) Hinge-moment characteristics unsatisfactory. (*c*) Restricts flap to split or Zap type.	14
10. Narrow ailerons behind 26 per cent. slotted flap.	12*f*, 13	$b/2 \times 0{\cdot}1c$	(*a*) All characteristics satisfactory, flaps up.	(*a*) As flaps are lowered beyond 30 deg. response and rolling action rapidly deteriorate. (*b*) Hinge moments are large and negative flaps down. (*c*) Adverse yawing moments are very large, flaps down.	9

TABLE 1B

Summary of Main Characteristics of Some Lateral Control Devices for Use with Partial Span Flaps

Type of control	Figs.	Probable dimensions required	Remarks		Refs.
			For	Against	
1. Short-span ailerons.	16	$0\cdot25b/2 \times 0\cdot4c$ to $0\cdot5c$	(*a*) Same general characteristics as normal ailerons. (*b*) Wind-tunnel tests give promise of some control beyond the stall. (*c*) Some lift can be obtained by down-rigging.	(*a*) Flight tests suggest tendency to overbalance in side-slip. (This should not occur if method of balancing employed reduces large b_1 (*e.g.* set-back hinge)). (*b*) Large inertia.	1, 6, 21, 22, 23
2. Combination of forward spoiler and short-span ailerons.	11*a* and *b*	Spoiler :— $0\cdot15b/2 \times 0\cdot1c$ Aileron :— $0\cdot2b/2$ to $0\cdot25b/2 \times 0\cdot4c$	(*a*) Small and probably favourable yawing moments. (*b*) Good control at high incidences. (*c*) Lag of spoiler should be largely masked by action of aileron.	(*a*) There may be difficulty in securing even response as spoiler comes into action. (*b*) Control system is complicated.	1, 24
3. Floating wing-tip ailerons.	17	About $0\cdot15$ wing-area.	(*a*) Response characteristics similar to to standard ailerons. (*b*) Favourable yawing moment. (*c*) Some control beyond the stall. (*d*) Makes smaller demands on wing torsional stiffness than standard ailerons.	(*a*) Possible lift on wing tips is largely lost. (*b*) To avoid flutter, it may be necessary to restrict the useful aileron movement. (*c*) Large inertia.	25, 26, 27.
4. Part of rear flap of large double-slotted flap used as aileron.	18, 19	$0\cdot45b/2 \times 0\cdot26c$ (Rigged down 15 deg).	(*a*) Characteristics, flaps up, similar to those of ordinary ailerons. (*b*) maximum lift, flaps down, only slightly less than that with full-span flaps.	(*a*) Great accuracy in construction probably required. (*b*) Complex mechanism of operation. (*c*) There may be difficulty in securing satisfactory hinge characteristics, flaps down. (*d*) Yawing moments, flaps down, probably large and unfavourable.	28, 29

APPENDIX I

By

R. R. DUDDY, B.Sc.

1. *Introduction.*—In the main part of this report reference is made to a number of wind-tunnel and flight investigations on unorthodox lateral controls which have since been completed. The objects of this Appendix are to summarise the results of those investigations and to add the more important results of later experiments on the same subject. The various types of control will be considered in the same order and under the same headings as in the main report.

A very useful resumé of American data on lateral control with large-span flaps is given in Reference 35.

2. *Slot-lip Ailerons.*—The type of slot-lip aileron in which the aileron is formed out of the top-surface lip of the slot of an N.A.C.A. slotted-flap (Fig. 3c) has been the subject of numerous wind-tunnel tests and flight tests in America (Ref. 35, Figs. A.11 to A.33). These results suggest that this type of spoiler can be made to give satisfactory lateral control although some difficulty may be experienced in obtaining reasonable hinge moments and the control tends to be over-sensitive when used with large flap deflections. The flight tests showed that although there was some lag and sluggishness the performance was only slightly worse than with conventional trailing edge ailerons.

Another type of slot-lip aileron consists of a slot through the wing with a hinged-plate spoiler on the top surface and a hinged scoop on the bottom surface so arranged that the slot is sealed with controls neutral. Wind-tunnel tests on this type of spoiler[34,35] show that sufficient rolling moments can be obtained and it may be possible to get satisfactory hinge moments by a suitable linkage between the spoiler and the scoop.

This spoiler arrangement (Fig. 20) has since been used successfully on an American operational reconnaissance aircraft, the *Kingfisher,* which was tested[36] in this country. In cruising flight lateral control is by slotted ailerons but for landing the ailerons are drooped and the spoilers provide full control. The spoiler hinge moments increased linearly with control movement throughout the speed range, the lag was measured to be about 0·05 sec., and the maximum $pb/2V$ was about 0·08 with ailerons and was greater than 0·10 with spoilers. In spite of this good performance the control was not popular with the pilots particularly when landing in gusty cross-wind conditions. It is interesting to note that the aircraft had 7 deg of dihedral and, as suggested in the main part of this report, this may have been responsible for the small lag but it may also have contributed to the difficulties in cross-wind landings.

2.2. *Spoilers on the " Courier " (Fig.* 5).—Following the unsatisfactory performance of this type of spoiler in flight, further wind-tunnel tests were made to try and improve the hinge moments and response to small control movements. The numerous modifications tested are described in Ref. 37; although some improvements were made the control was never entirely satisfactory and further flight work was abandoned.

2.3. *Retractable-Arc Spoilers* (Figs. 6, 7, 8).—The very large number of American wind-tunnel tests on retractable-arc and plug-type spoilers are summarised in Ref. 35 and similar development tests made by Blackburns are given in Ref. 34. All these tests have been directed towards improving the effectiveness of the control for small displacements and producing reasonable hinge-moment curves. It appears difficult to satisfy the requirements for the full range of incidences and flap deflections with any simple form of spoiler.

2.3.1. *Retractable-arc spoilers on the "Falcon"* (*Fig.* 9).—The modifications made to these spoilers[38] following the initial flight trials were designed to

(*a*) eliminate the unpleasant hinge moments by making the circular arcs truly concentric with their hinge lines,

(*b*) reduce the inertia of the system,

and (*c*) reduce friction and backlash in the operating circuit.

The modified control had negligible feel but was considered to be reasonably satisfactory. The chief disadvantage of the scheme is the variation in response with speed. At high speeds, the response is initially poor, followed by a rather sudden increase in effectiveness, but at cruising speed the control was very satisfactory. At low airspeeds the initial response is again poor with flaps up, but with full-span split flaps the response is quite adequate. There is no appreciable time lag between the start of the control movement and the start of the roll.

2.3.2. *Retractable-arc spoilers on a high-lift "Lysander"* (*Fig.* 10).—After a few tests, in which the *Lysander* took off for a few seconds and then relanded, the pilot decided that the standard of control was not good enough to permit further flight trials. The unsatisfactory characteristics included an initial heaviness with poor response followed by a sudden increase of response and lightening of the stick force. This gave a feeling of overbalance to the control, which was probably accentuated by the large amount of friction in the control circuit.

One half of the full-scale aircraft was put in the 24-ft. diameter open-jet wind-tunnel to investigate possible methods of improving the control. It was concluded that a complete redesign of the control operating mechanism would be required and because of more urgent wartime activities the experiment had to be abandoned.

3. *Slotted Ailerons inset in a Slotted Flap*.—This arrangement is similar to the one shown in Fig. 12f except that the plain ailerons are replaced by slotted ones in an endeavour to retain aileron effectiveness at large flap deflections. The particular installation shown in Fig. 21 was tested in flight[39,40] on the High Lift M.18 aircraft. Rolling tests were made down to a speed corresponding to an engine-off lift coefficient of 2·7. It was found that, even with the flap deflection restricted to 30 deg, there was a marked reduction in the maximum rate of roll at high-lift coefficients. This was thought to be due to the large adverse yawing moment which was produced by the ailerons at high lift coefficients in conjunction with a large value of rolling moment due to rate of yaw (l_r). It is interesting that the large adverse yawing moments were not commented on by pilots making general handling tests but large rates of yaw were measured during the rolling tests.

In order to improve the rolling power with flaps deflected, the hinged-plate spoilers shown in Fig. 21 were fitted. The spoilers were arranged to operate in conjunction with the ailerons and the resulting rolling moments were more than adequate even at the highest lift coefficients. The adverse yawing moments were slightly increased but the ratio of yawing moment to rolling moment was very much reduced. The measured lag and sluggishness were very small under all flight conditions; a typical record obtained during rapid aileron application is given in Fig. 21. Although, as often happens with experimental light aircraft, excessive friction in the control circuit made it impossible to obtain an appreciation of the feel of the control, the arrangement is very promising.

An alternative arrangement using an inset aileron was tested on the Youngman-Baynes experimental aircraft (Fig. 22); the outboard half of the full-span main flap carries the slotted aileron and the inboard half has an auxiliary slotted flap. The flight tests on this scheme[41] gave very encouraging results; there was negligible lag and the response and feel were both satisfactory. If anything, the performance with flaps down was better than with flaps up and in both conditions the rolling power was more than adequate.

There is a considerable sacrifice in absolute maximum lift coefficient because of the limited deflection of the main flap and the fairly large proportion of flap span occupied by the aileron. The flight results suggest, however, that the aileron span could be reduced by up to 20 per cent and still retain sufficient aileron power, thus allowing a greater span for the double-slotted flap.

4. *Lateral Control with Nearly-Full-Span Flaps.*—4.1. *Short Span, Wide Chord Ailerons* (Fig. 16.)—Flight experience with ailerons of this unconventional shape was obtained at the Royal Aircraft Establishment on a *Master I* aircraft. The special ailerons had a span of only $0 \cdot 21\ b/2$ and a chord of $0 \cdot 4c$, there was no forward balance and it was originally hoped that the response effect, due to the large negative value of b_1, combined with a geared tab would give satisfactory hinge moments. In actual fact the feel was most unpleasant; large forces were required to start a roll but much less force was required to hold a steady rate of roll. This was believed to be due to a combination of large response effect and high control inertia. Although the aileron power was insufficient, there was no appreciable lag or sluggishness.

The control was later modified:

(*a*) to reduce the inertia,

(*b*) to increase the travel from ± 15 deg to ± 25 deg,

and (*c*) to fit a large spring tab.

To obtain satisfactory control forces at the large control deflections the spring in the tab control was relatively weak and in fact the control approximated to a servo-tab system. These modifications caused a considerable improvement in the hinge moments and feel of the aileron, the unpleasant effects of the high inertia being very much reduced. The rolling power was still inadequate, the increase due to the greater travel having been counterbalanced by the large increase in tab size. In spite of this defect it is considered that the control showed promise and might have been entirely successful if partial balance had been obtained by using a set back hinge. This would have reduced the size of tab required and so given greater rolling moments.

The difficulty with this form of control during sideslips, due to the leading wing tending to " dig in " as described in the main part of the report, was never experienced with the *Master*, possibly due to the fairly large dihedral angle of 6 deg.

4.2. *Combination of Spoilers and Short-Span Ailerons* (Figs. 11a and b).—Two fairly heavily loaded aircraft have been flown with a combination of circular-arc spoilers just forward of the flaps and small-feel ailerons. The first, an American night fighter (*Black Widow*) is shown in Fig. 23a[42] and the second was a modified British heavy bomber (*Halifax*) shown in Fig. 23b[43]. The *Black Widow* installation was generally considered to be very successful. There was adequate rolling moment at all speeds and no appreciable lag but the control had considerable inertia which made it difficult to make small and rapid control movements. During the development of the control in America it was found that if the spoiler slot were sealed then the flap gap also had to be sealed to prevent a large loss in control effectiveness for small movements with the flaps deflected.

On the *Halifax* the control was satisfactory at cruising and high speeds but as the speed was reduced below about 130 m.p.h. A.S.I. the rolling moment was apparently reduced and there was appreciable lag. The spoiler projection on the *Halifax* was less than on the *Black Widow*, and the overlap between the spoiler and aileron would also help to account for the lower rolling moments.

5. *Discussion.*—No lateral control which provides rolling moment by simply spoiling the lift on one wing has proved entirely successful in flight. As it has been pointed out the overall loss in lift necessarily involved, when rolling with pure spoiler control, can cause difficulty. This feature has been continually criticised by pilots because the loss in height whilst " picking up a wing " during a landing in gusty conditions adds to the difficulties of controlling the approach

path. Since the height lost during rolling will be a function of the percentage-lift change due to the spoilers, it seems probable that this characteristic would be less pronounced when using very ambitious high-lift devices.

The most successful schemes have included some form of aileron and although this necessarily results in a restriction on either the flap span or flap deflection it appears to be worth while as

(*a*) it reduces the apparent lag,
(*b*) it can be used to provide feel,
and (*c*) it is convenient for providing lateral trimming.

In addition there is some evidence suggesting that it may be difficult to prevent wing dropping at the stall if large local lift coefficients are used right out to the tip of the wing.

These arguments lead to the suggestion that spoilers should be regarded as a device for augmenting the rolling power of the ailerons. To enable the use of large-span flaps it is further suggested that the ailerons should be either

(*a*) wide-chord and short-span, *e.g.* $0 \cdot 35c \times 0 \cdot 15b/2$,
or (*b*) inset in a full-span flap, as on the High Lift M.18 or Youngman-Baynes aircraft.

The most useful type of spoiler is probably the circular-arc type which is relatively simple and should not introduce any hinge-moment problems. There appear to be two alternative positions for the spoiler:

(i) just forward of the flap gap, where it will be least subject to lag but it may be ineffective for small displacements,
or (ii) at about $0 \cdot 25c$ aft of the wing-leading edge, where the size of spoiler, for a given rolling moment, will be a minimum, thus giving least control inertia, but the spoiler will tend to give lag and sluggishness.

Probably the greatest difficulty in designing a combined aileron and spoiler lateral control is deciding how far the aileron size can be reduced before the lag and sluggishness of the spoiler become objectionable.

When designing a lateral control using lift-spoilers alone there is considerable difficulty in meeting the feel requirement. If the hinge moments are reduced to very small values by using the circular-arc type of spoiler, then it appears difficult to obtain a low enough control inertia. With slot-lip ailerons the inertia can be kept down but the hinge moments are usually large and vary irregularly with control displacement. If the complications of power operation can be tolerated then the problem of designing a satisfactory spoiler becomes very much simpler.

Whilst lateral control with high-lift devices by lift-spoilers alone is not very promising it should be remembered that spoilers may be particularly useful at high speeds on aircraft with sweptback wings.

6. *Conclusions.*—The general conclusions of the main part of the report are confirmed by the additional evidence which has since been collected.

Although no lateral control which depends on spoilers alone has been entirely satisfactory, the *Kingfisher* scheme was certainly quite adequate. The main difficulties are still the provision of smooth response and reasonable feel.

Flight tests with wide-chord ailerons indicate that this type of control can be quite satisfactory and it is probable that between 80 and 85 per cent of the maximum possible flap span can be used provided a simple spoiler is added to give additional rolling moment.

Satisfactory rolling control has been obtained in flight with full-span flaps by slotted-ailerons inset in large-chord slotted flaps. At high-lift coefficients the adverse yawing moments are quite large but they are not objectionable.

REFERENCES

No.	*Authors*	*Title, etc.*
1	Weick, Soulé, Hartley and Gough ..	A Flight Investigation of the Lateral Control Characteristics of Short-Wide Ailerons and Various Spoilers with Different Amounts of Wing Dihedral. N.A.C.A. Technical Report No. 494. 1934.
2	Soulé and McAvoy	Flight Investigation of Lateral Control Devices for Use with Full-span Flaps. N.A.C.A. Technical Report No. 517. 1935.
3	Shortal	Wind-tunnel and Flight Tests of Slot-lip Ailerons. N.A.C.A. Technical Report No. 602. 1937.
4	Prandtl	Aerodynamic Theory. Vol. III, pp. 95–102.
5	Gates and Irving	An Analysis of Aileron Performance. R.A.E. Report No. B.A. 1624. July, 1940.
6	Weick and Wenzinger	Ordinary Ailerons on Rectangular Wings. N.A.C.A. Technical Report No. 419. 1932.
7	Weick and Shortal	Development of the N.A.C.A. Slot-lip Aileron. N.A.C.A. Technical Note No. 547. 1935.
8	Shortal	Effect of Retractable Spoiler Location on Rolling and Yawing-moment Coefficients. N.A.C.A. Technical Note No. 499. 1935.
9	Wenzinger and Bamber	Wind-tunnel Tests of Three Lateral Control Devices in Combination with a Full-span Slotted Flap on an N.A.C.A. 23012 Aerofoil. N.A.C.A. Technical Note No. 659. 1938.
10	Wetmore	Flight Tests of Retractable Ailerons on a Highly-tapered Wing. N.A.C.A. Technical Note No. 714. 1939.
11	Rogalls and Swanson	Wind-tunnel Development of a Spoiler-slot Aileron for a Wing with a full-span Slotted Flap. N.A.C.A. Advance Report (A.R.C. 4836). (Unpublished). 1940.
12	Wind tunnel staff of Blackburn Aircraft Ltd.	Further Model Experiments on an Aeroplane fitted with a Large-chord Slotted Flap. Report W.T. 40/40a. (Unpublished).
13	Lyon and Pindar	A Comparison between Different Types of Slotted Flaps. R.A.E. Report No. B.A. 1615 (4635). (Unpublished). July, 1940.
14	Dearborn and Soulé	Full Scale Wind-tunnel and Flight-tests of a Fairchild 22 Aeroplane equipped with a Zap Flap and Zap Ailerons. N.A.C.A. Technical Note No. 596. 1937.
15	House	The Effects of Partial-span Plain Flaps on the Aerodynamic Characteristics of a Rectangular and a Tapered Clark Y Wing. N.A.C.A. Technical Note No. 663. 1938.
16	Wenzinger	The Effect of Partial-span Split Flaps on the Aerodynamic Characteristics of a Clark Y Wing. N.A.C.A. Technical Note No. 472. 1933.
17	Wenzinger	The Effects of Full-span and Partial-span Split Flaps on the Aerodynamic Characteristics of a Tapered Wing. N.A.C.A. Technical Note No. 505. 1934.
18	House	The Effects of Partial-span Slotted Flaps on the Aerodynamic characteristics of a Rectangular and a Tapered NACA 23012 Wing. N.A.C.A. Technical Note 719. 1939.
19	Hollingdale	Aerodynamic Characteristics of Tapered Wings with Flaps and Slots. R. & M. 1774. 1938.
20	Irving, Warsap, Batson and Gummer	Some Aerodynamic Characteristics of Tapered Wings fitted with Flaps of Various Spans. R. & M. 1796. 1936.
21	Weick and Shortal	Straight and Skewed Ailerons on Wings and Rounded Tips. N.A.C.A. Technical Note No. 445. 1938.
22	Diprose and Nayler	24-ft. Wind-tunnel Tests on a F.A.A. High-lift Model I. Tests without Tail Unit. B.A. Departmental Note—Large Wind Tunnel No. 41. 1940.

REFERENCES—*contd.*

No.	*Authors*	*Title, etc.*
23	Weick and Harris	Skewed Ailerons On Rectangular Wings. N.A.C.A. Technical Report No. 444. 1932.
24	Weick and Shortal	Spoilers and Ailerons on Rectangular Wings. N.A.C.A. Technical Report No. 439. 1932.
25	Weick and Harris	Floating Tip Ailerons on Rectangular Wings. N.A.C.A. Technical Report No. 424. 1932.
26	Weick and Harris	Various Floating-tip Ailerons on both Rectangular and Tapered Wings. N.A.C.A. Technical Note No. 458. 1933.
27	Soulé and Gracey	A Flight Comparison of Conventional Ailerons on a Rectangular Wing and of Conventional and Floating-tip Ailerons on a Tapered Wing. N.A.C.A. Technical Report 630.
28	Harris and Recant	Wind-tunnel Investigation of NACA 23012, 23021 and 23030 Aerofoils equipped with 4 per cent. Chord Double-slotted Flaps. N.A.C.A. Advance Report (A.R.C. 4834). (Unpublished). 1940.
29	Young	A Further Comparison of High-lift Devices. A.R.C. 5089. (Unpublished). 1941.
30	Irving, Warsap and Gummer ..	Model Experiments on a Double-hinge Balance Flap arranged as an Upper surface Spoiler Aileron. A.R.C. Report No. 2272. (Unpublished). 1936.
31	Wenzinger	Wind-tunnel Investigation of the Aerodynamic Balancing of Upper-surface Ailerons and Split Flaps. N.A.C.A. Technical Report 549. 1935.
32	Serby and Hufton	Full-scale Tests of a Retractable-arc Flap on a RAF 48 Wing fitted on a Parasol Monoplane. A.R.C. 2581. July, 1936.
33	Gates	Note on Differential Gearing as a means of Aileron Balance. R. & M. 2526. December, 1940.
34	Blackburn Aircraft Limited ..	Further Wind-tunnel Developments of the Spoiler as a Form of Lateral Control. Blackburn Report W.T. 84/42.
35	Fischel and Ivey	Collection of Test Data for Lateral Control with Full-span Flaps. N.A.C.A. Technical Note No. 1404. 1948.
36	Ewans, Stewart & Warren	Handling and Lateral Control (Spoiler and Aileron) Tests on a Kingfisher. A.R.C. 7289. (Unpublished). September, 1943.
37	Duddy & Gray	Tunnel Tests on " Courier " Type Spoiler Control. R.A.E. Departmental Note No. Aero LWT.60. November, 1941.
38	Kerr	Flight Tests on a " Falcon " with Spoiler Lateral Control. R. & M. 2491. December, 1941.
39	Duddy..	Rolling Characteristics of the High Lift M.18. A.R.C. 8381. (Unpublished). September, 1944.
40	Crabbe..	Rolling Tests on the High Lift M.18 with Spoilers. A.R.C. 9952. (Unpublished). June, 1946.
41	Lean	Flight Tests on the Youngman-Baynes High-lift Experimental Aircraft. R.A.E. Report No. Aero....... December, 1949.
42	Ashkenas	The Development of a Lateral Control System for use with Large-span Flaps. N.A.C.A. Technical Note No. 1015. January, 1946.
43	Morrall	Tests of Halifax B VI fitted with Spoiler Aileron Controls. A.R.C. 11, 882. (Unpublished). August, 1948.

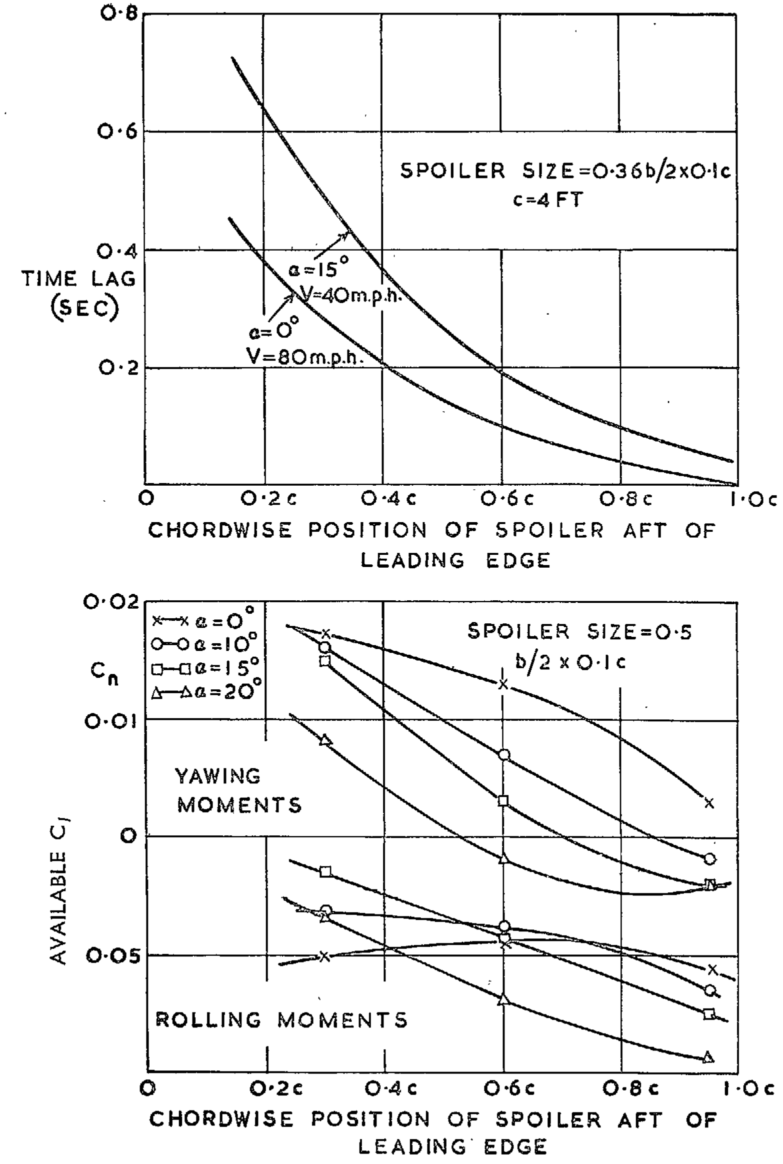
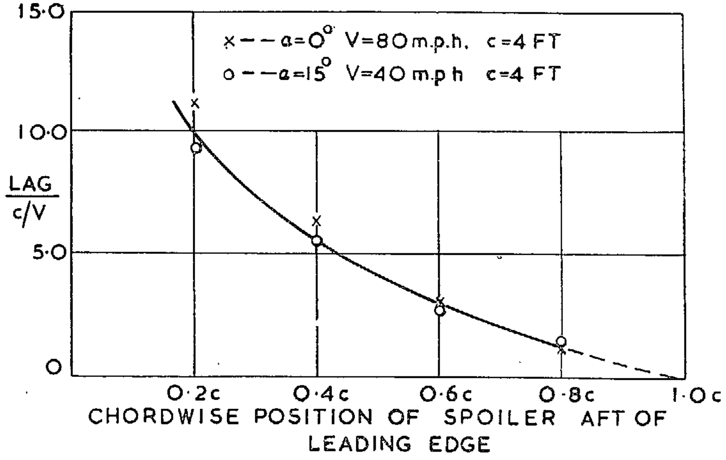
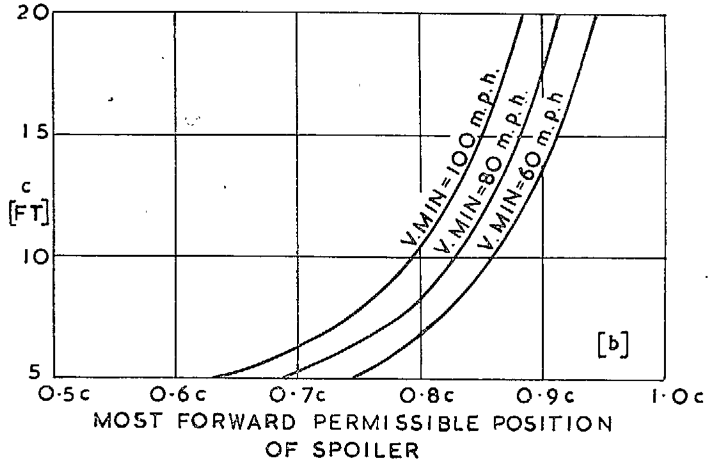


FIG. 1. Measured Lag and Available Rolling and Yawing Moments for Simple Retractable-arc Spoiler at Various Chord-wise Positions.

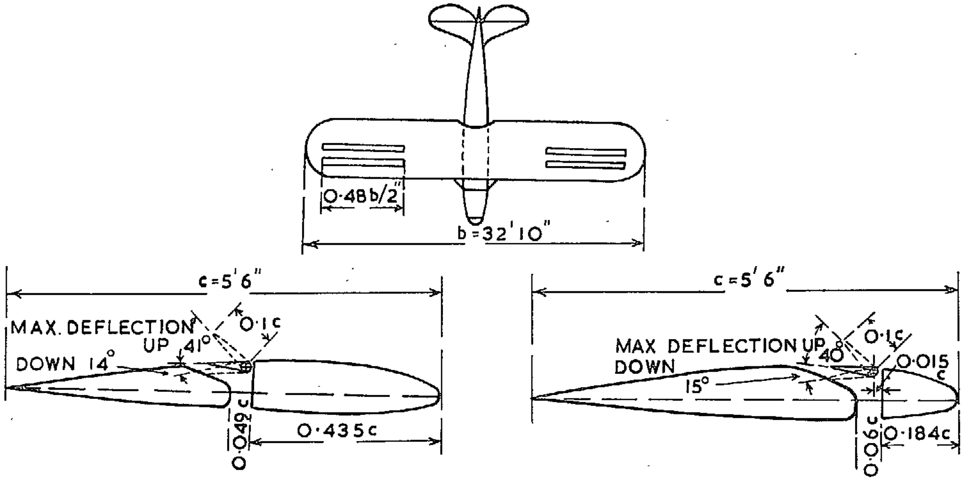


[a] LAG [NON-DIMENSIONAL] OF SIMPLE SPOILER AT VARIOUS CHORDWISE POSITIONS

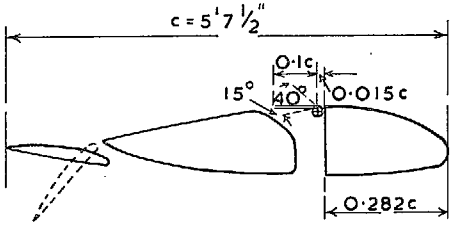


[b] PERMISSIBLE POSITIONS OF SIMPLE SPOILER TO GIVE NEGLIGIBLE LAG

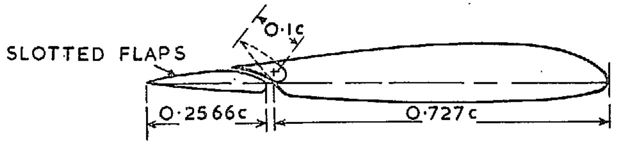
FIG. 2.



(a) SLOT-LIP AILERONS TESTED ON FAIRCHILD 22 AEROPLANE



(b) SLOT-LIP AILERON TESTED ON A WI-A AEROPLANE



(c) SPECIAL FORM OF SLOT-LIP AILERON TESTED IN NACA 7'x10' TUNNEL

FIG. 3. Slot-lip Ailerons.

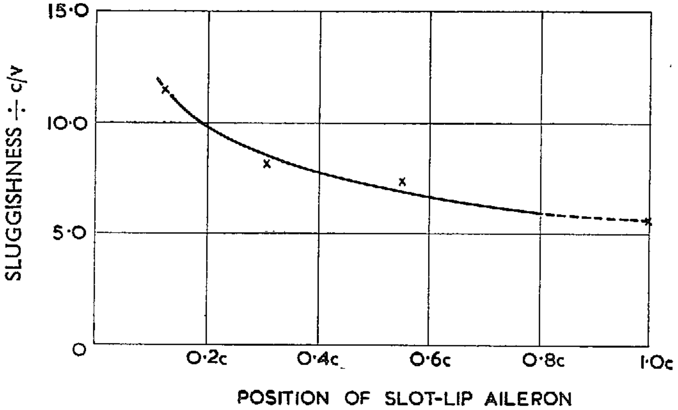
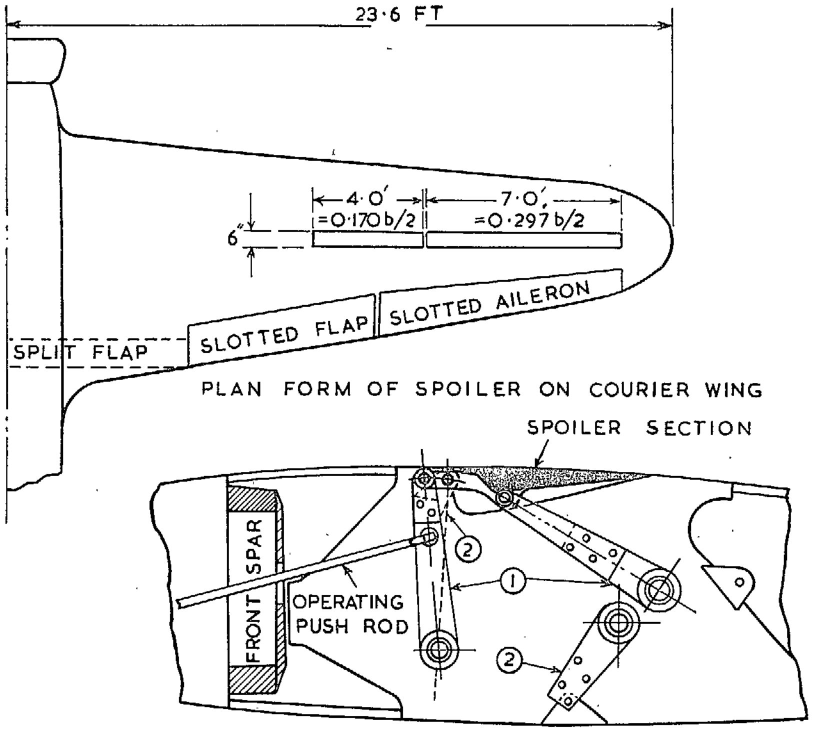


FIG. 4. Sluggishness of Slot-lip Ailerons.



PLAN FORM OF SPOILER ON COURIER WING

SPOILER OPERATING LINKAGES
① AND ② ARE ALTERNATIVE LINKAGES

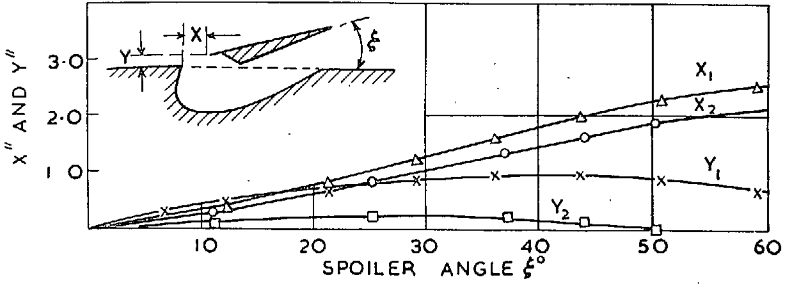
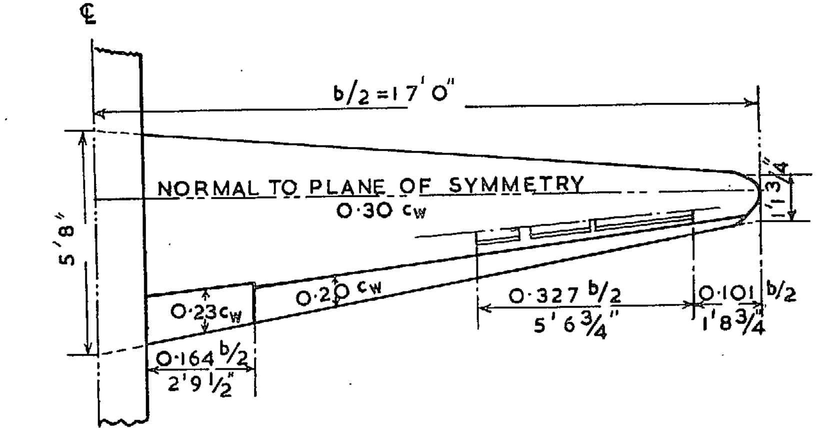


Fig. 5. Spoiler on Courier.



SKETCH OF PLAN FORM OF WING OF MODIFIED FAIRCHILD 22 AEROPLANE

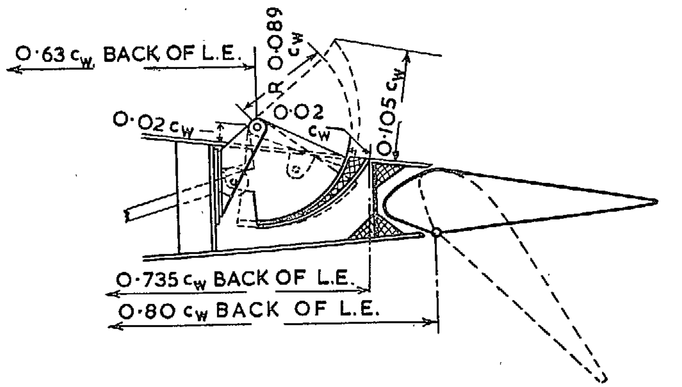


Fig. 6. Section View of Retractable-arc Ailerons and Flaps as installed on Modified Fairchild 22 Aeroplane.

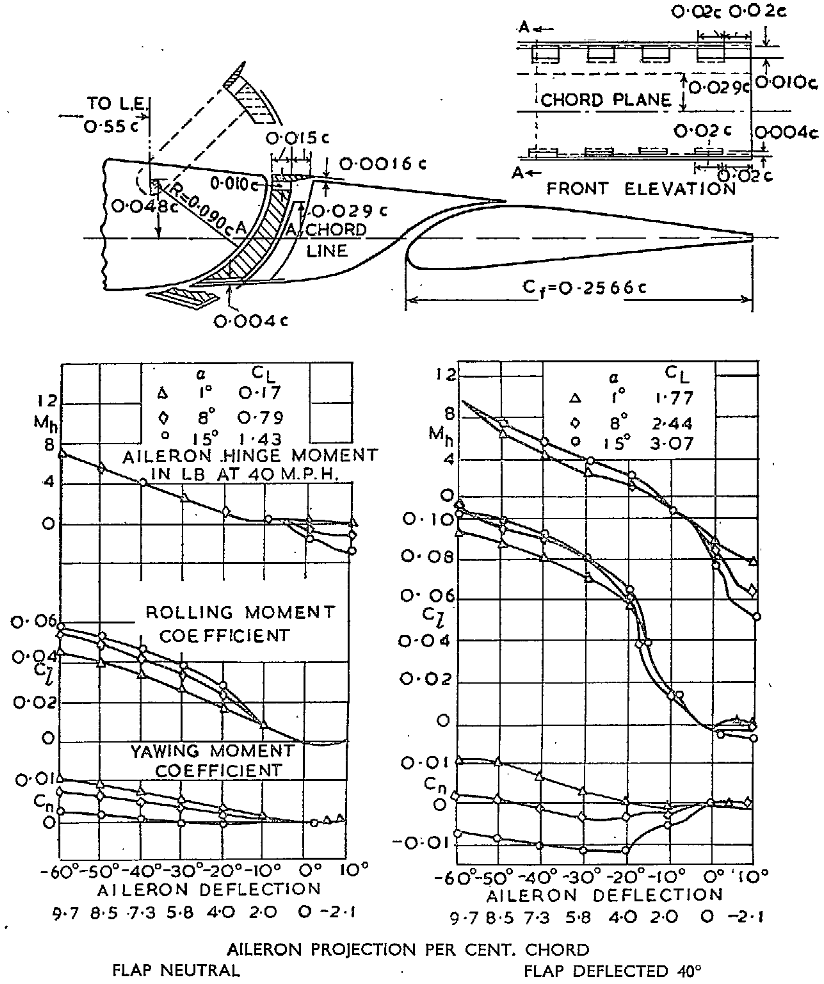


FIG. 7. 0·375$b/2$ Retractable-arc Spoiler on an NACA 23012 Wing with a 0·2566c Full-span Slotted Flap. Arrangement A.

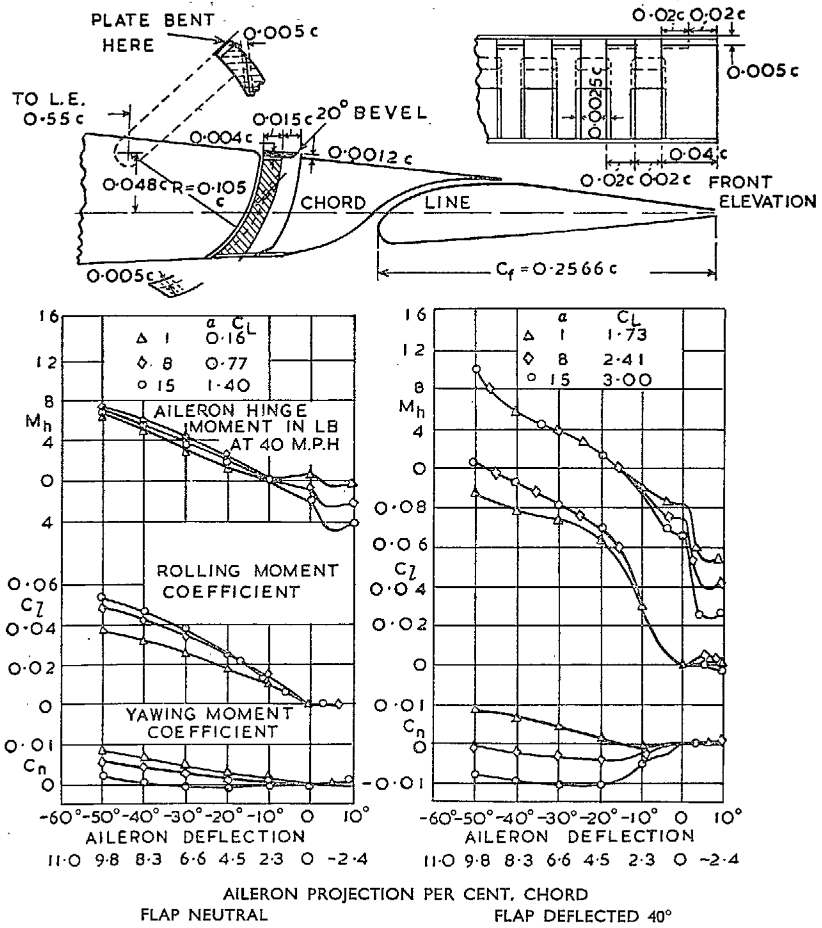


FIG. 8. 0·375 $b/2$ Retractable-arc Spoiler on an NACA 23012 Wing with a 0·2566c Full-span Slotted Flap. Arrangement B.

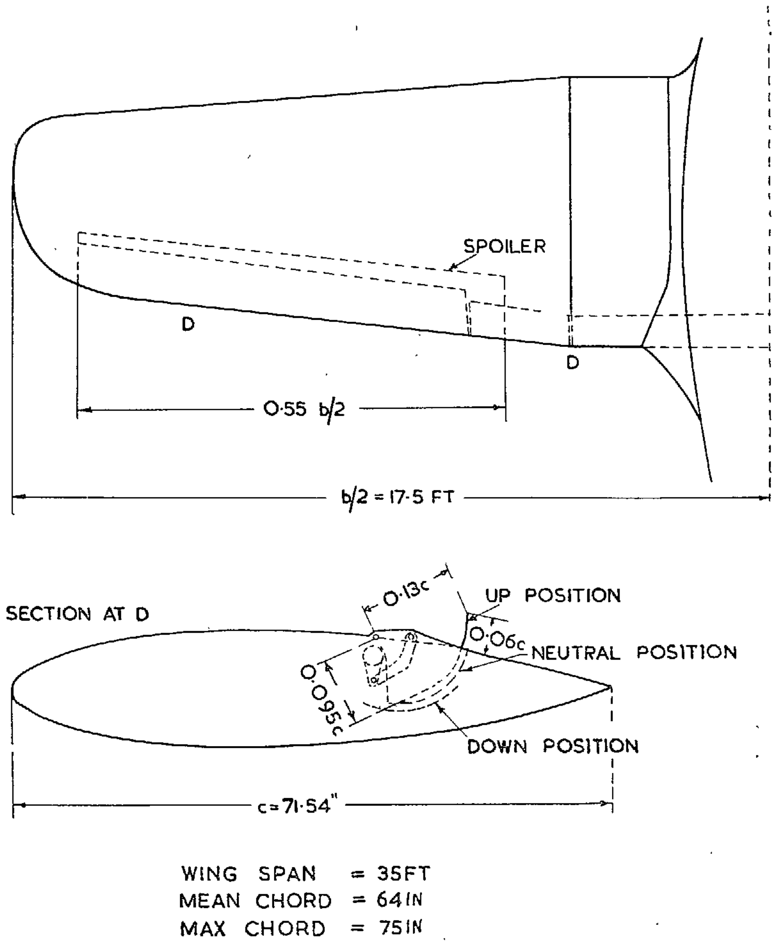


FIG. 9. Retractable-arc Ailerons on Falcon (40 per cent. Piercy Section).

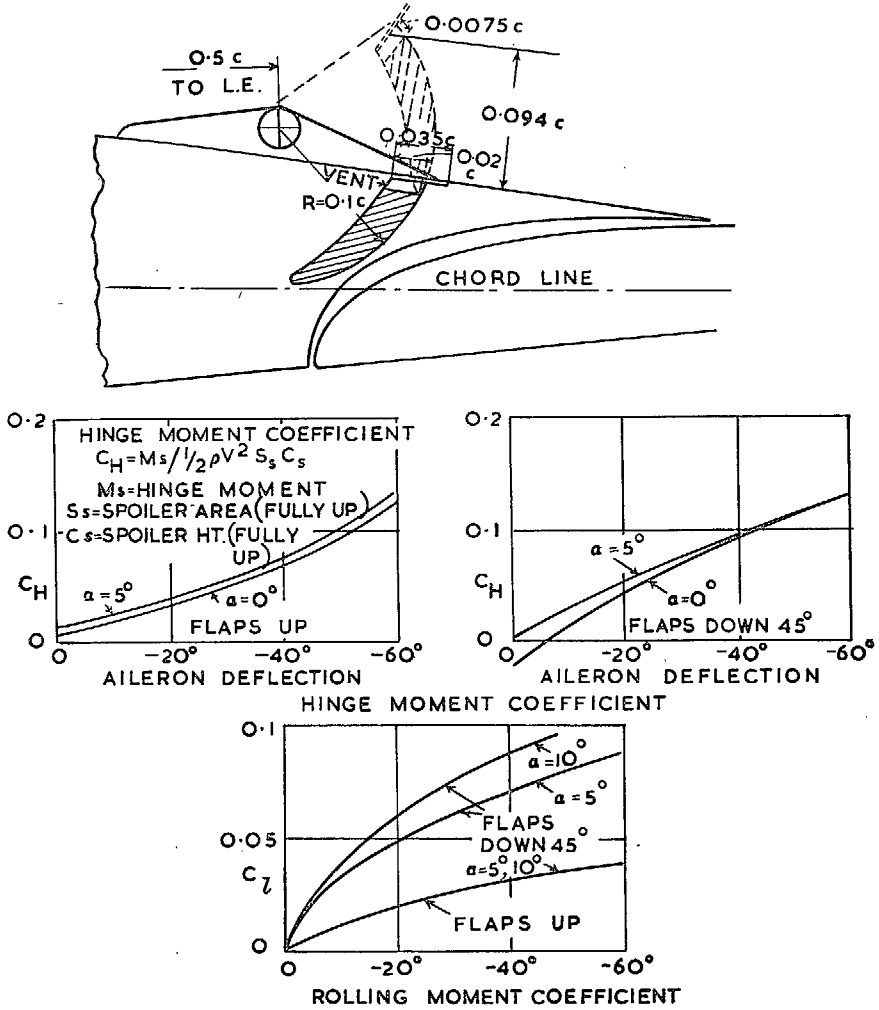
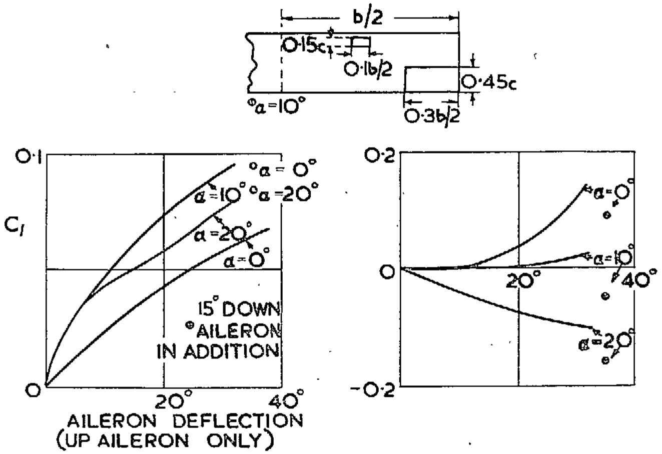
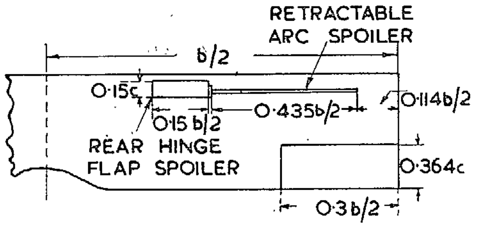


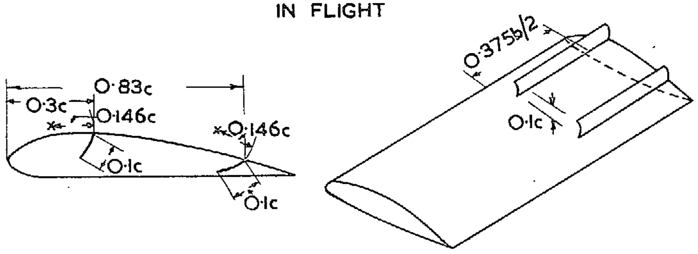
FIG. 10. Blackburn Retractable-arc Spoiler (Span = 0·27 $b/2$).



(a) ROLLING AND YAWING MOMENTS MEASURED IN WIND TUNNEL FOR COMBINATION OF SHORT WIDE AILERONS AND SMALL REAR HINGE SPOILER

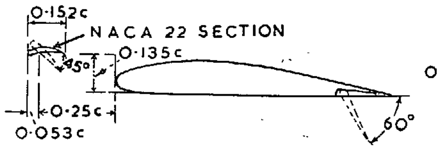


(b) SPOILERS AND SHORT SPAN AILERONS TESTED IN COMBINATION IN FLIGHT

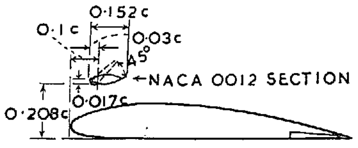


(c) COMBINATION OF FORWARD AND REAR RETRACTABLE ARC SPOILERS TESTED IN THE NACA 7'×10' WIND TUNNEL

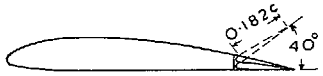
FIG. 11. Some Combinations of Lateral-control Devices



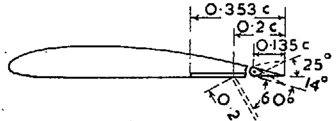
(a) CONTROLLABLE AUXILIARY AEROFOIL



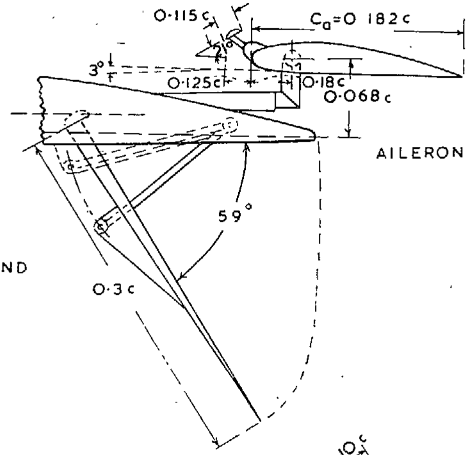
(b) EXTERNAL AILERON



(c) UPPER SURFACE AILERON

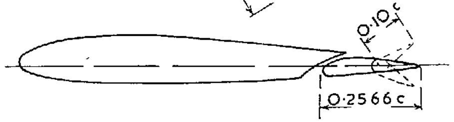


(d) NARROW CHORD AILERONS WITH ZAP TYPE FLAP



(e) ZAP AILERON AND ZAP FLAP

AILERON SPAN = 0·54 b/2



(f) PLAIN NARROW CHORD AILERON BEHIND SLOTTED FLAP

FIG. 12. Some Devices for Lateral Control with Full-span Flaps.

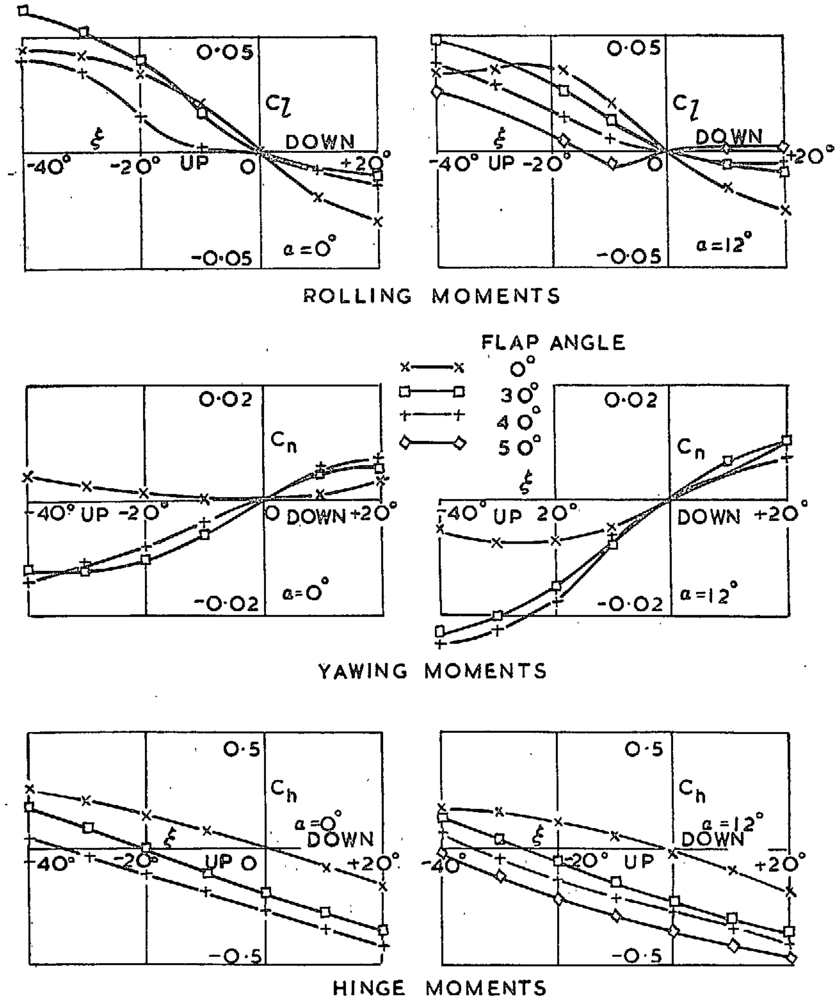


FIG. 13. Plain Ailerons behind Full-span 0·26*c* NACA Slotted Flap.

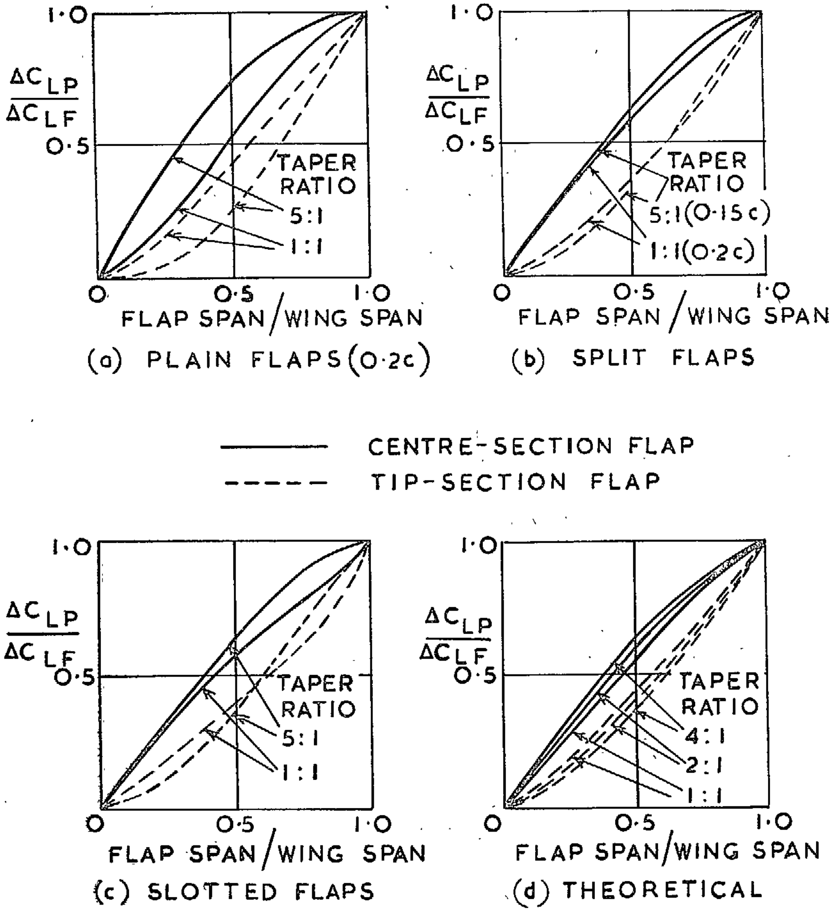


FIG. 14. Experimental and Theoretical Values for Ratio of Lift Increment of Part-span Flap (ΔC_{LP}) to Lift Increment of Full-span Flap (ΔC_{LF}).

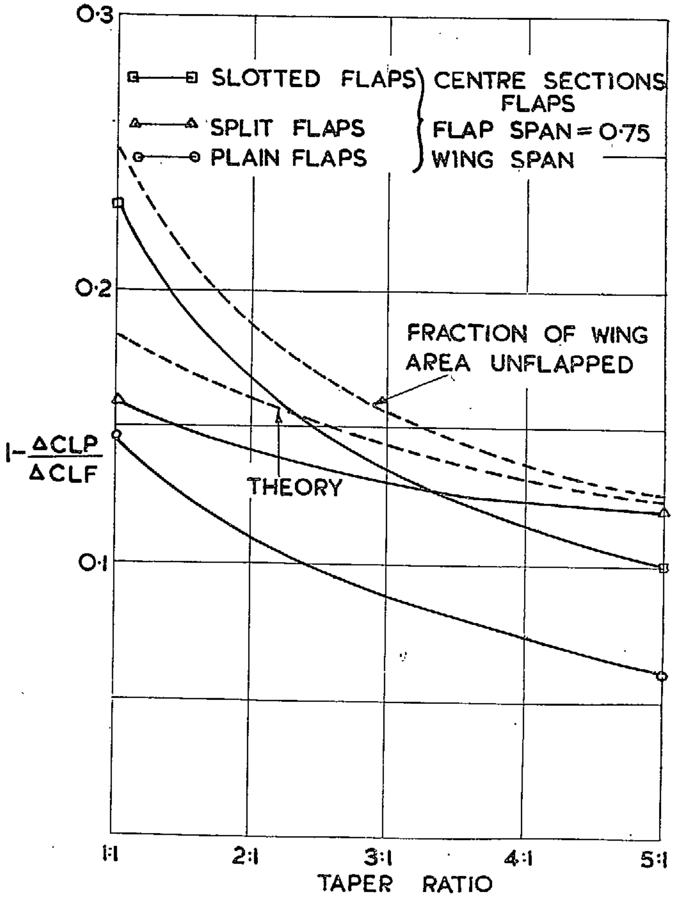
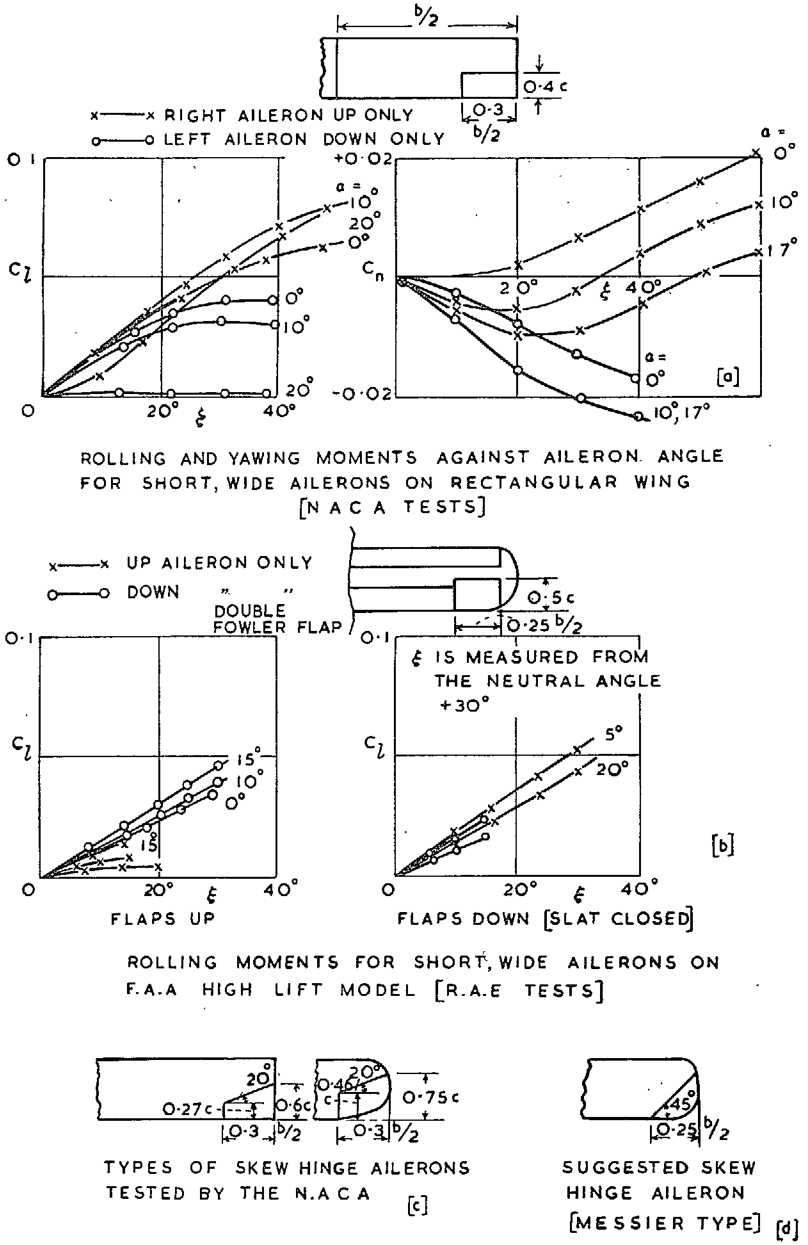


FIG. 15. Fractional Loss of Lift Increment using 75 per cent. Span Centre-section Flaps instead of Full-span Flaps.



ROLLING AND YAWING MOMENTS AGAINST AILERON ANGLE FOR SHORT, WIDE AILERONS ON RECTANGULAR WING [N A C A TESTS]

ROLLING MOMENTS FOR SHORT, WIDE AILERONS ON F.A.A HIGH LIFT MODEL [R.A.E TESTS]

TYPES OF SKEW HINGE AILERONS TESTED BY THE N.A.C.A [c]

SUGGESTED SKEW HINGE AILERON [MESSIER TYPE] [d]

FIG. 16. Short-span Ailerons.

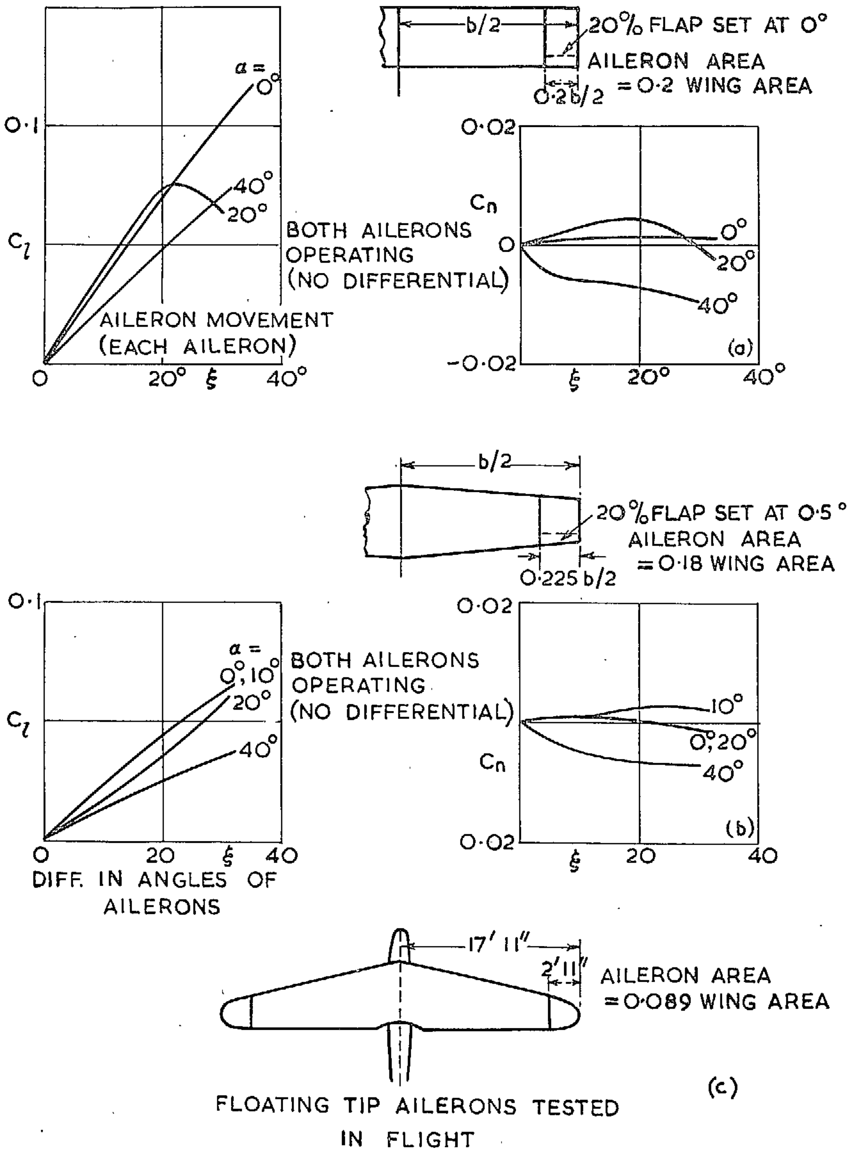


Fig. 17. Floating-tip Ailerons.

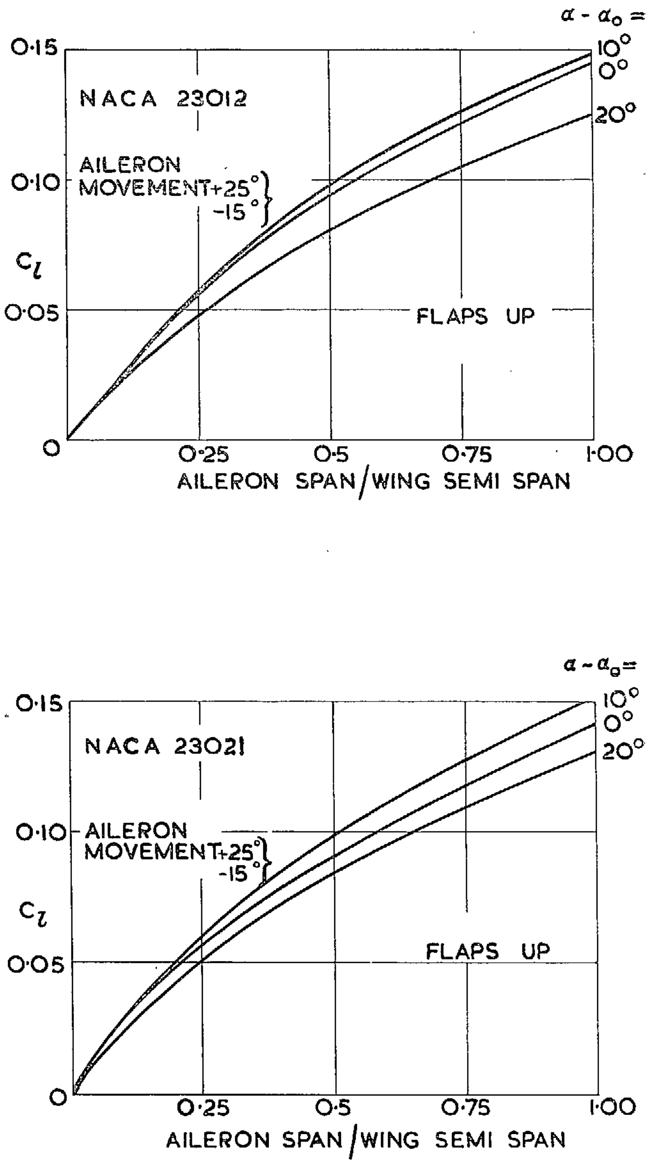


Fig. 18. Part of 2nd Flap of Large NACA Double-slotted Flap used as Aileron. Available Rolling Moments for Various Aileron Spans, Flaps Up.

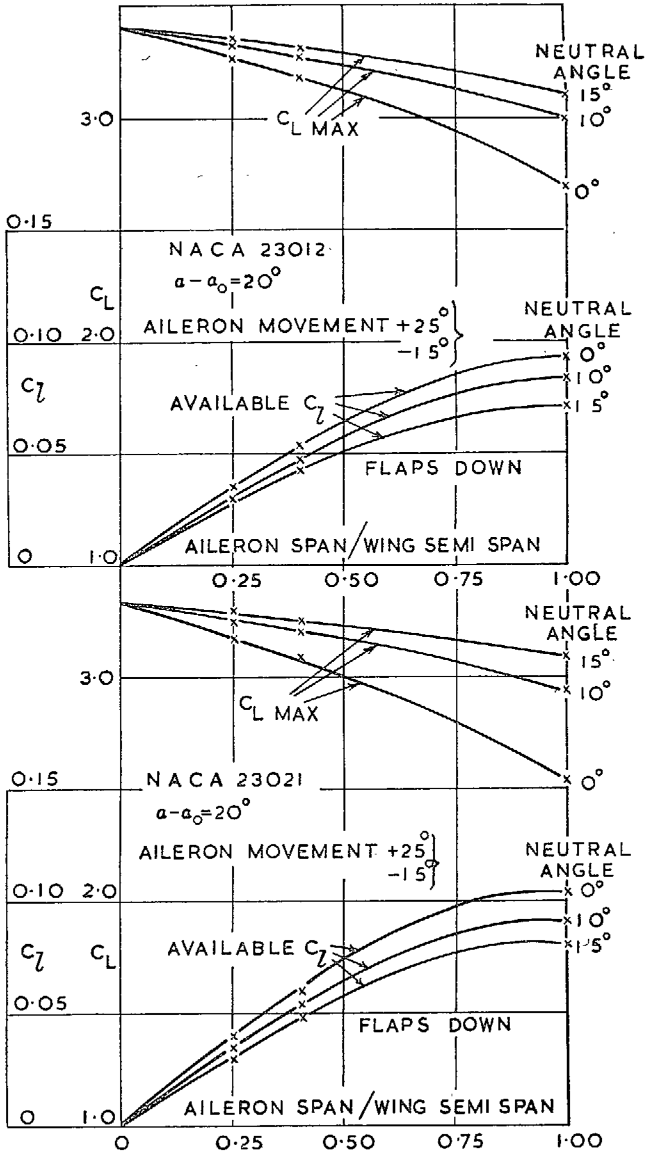


FIG. 19. Part of 2nd Flap of Large NACA Double-slotted Flap used as Aileron. Available Rolling-moments and Lift Coefficients for Various Aileron Spans ($\alpha - \alpha_0 = 20$ deg.). Flaps Down.

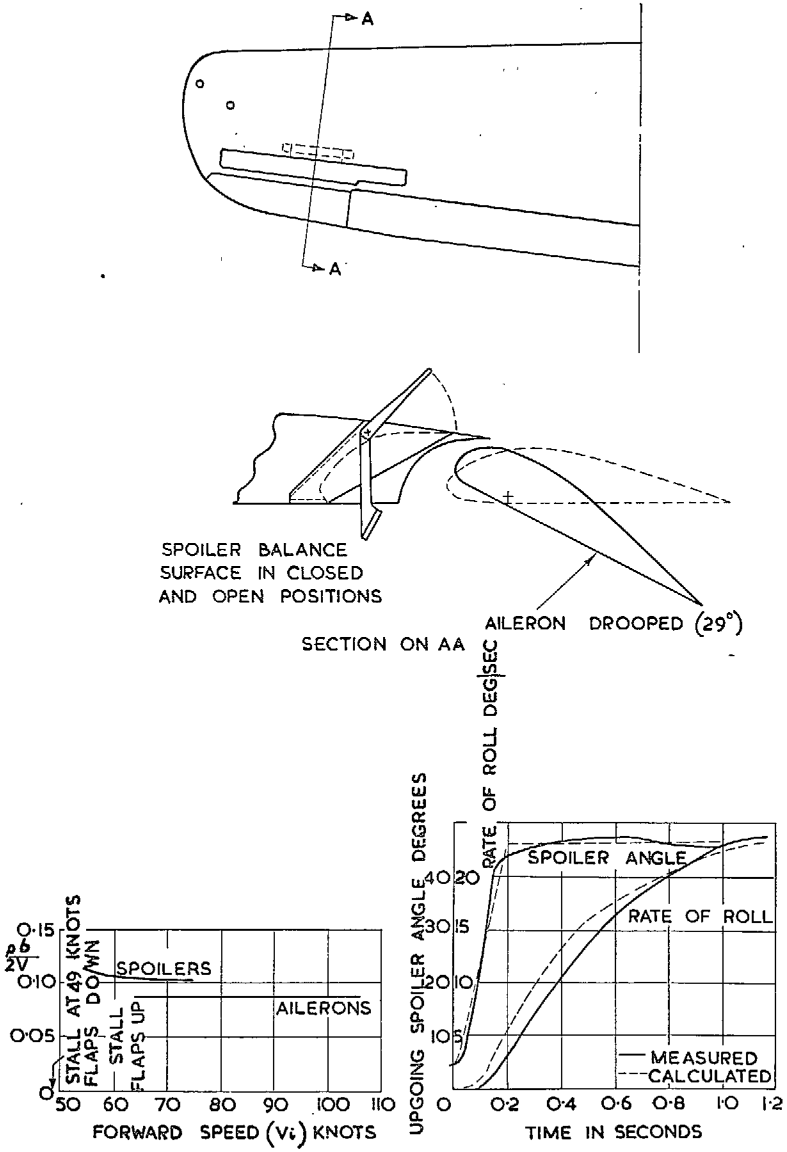
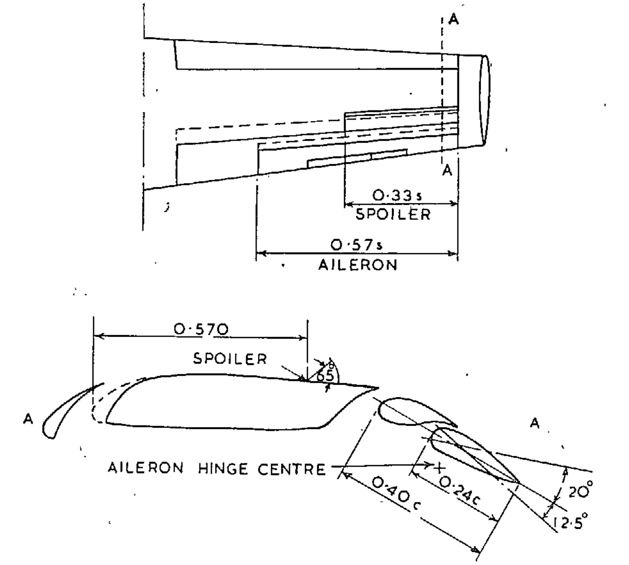


FIG. 20. Slot-lip Ailerons on Kingfisher.



SECTION OF WING SHOWING FLAP AND SLAT ARRANGEMENT AND POSITION OF SPOILER

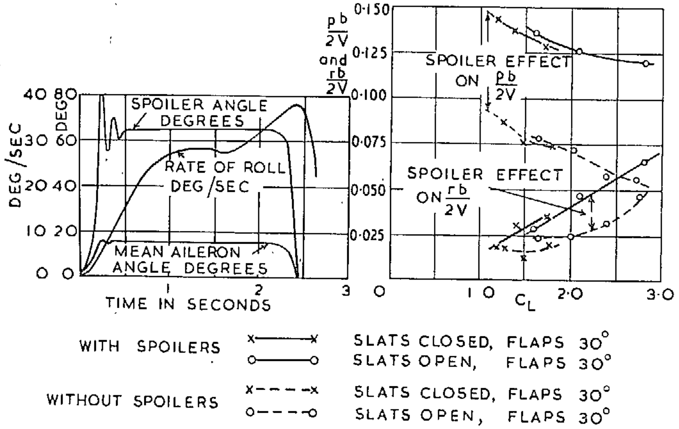


FIG. 21. Inset Aileron and Spoiler on High Lift M.18.

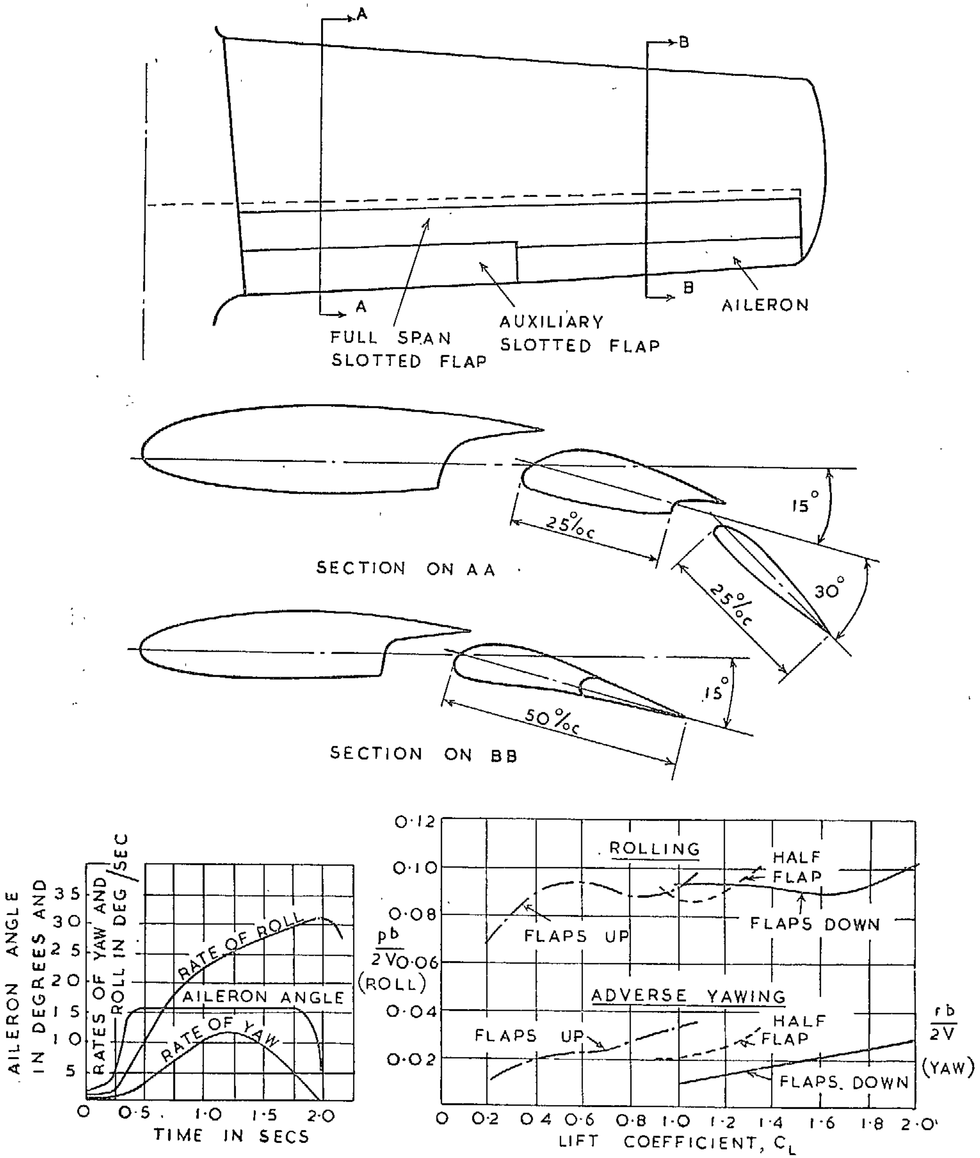
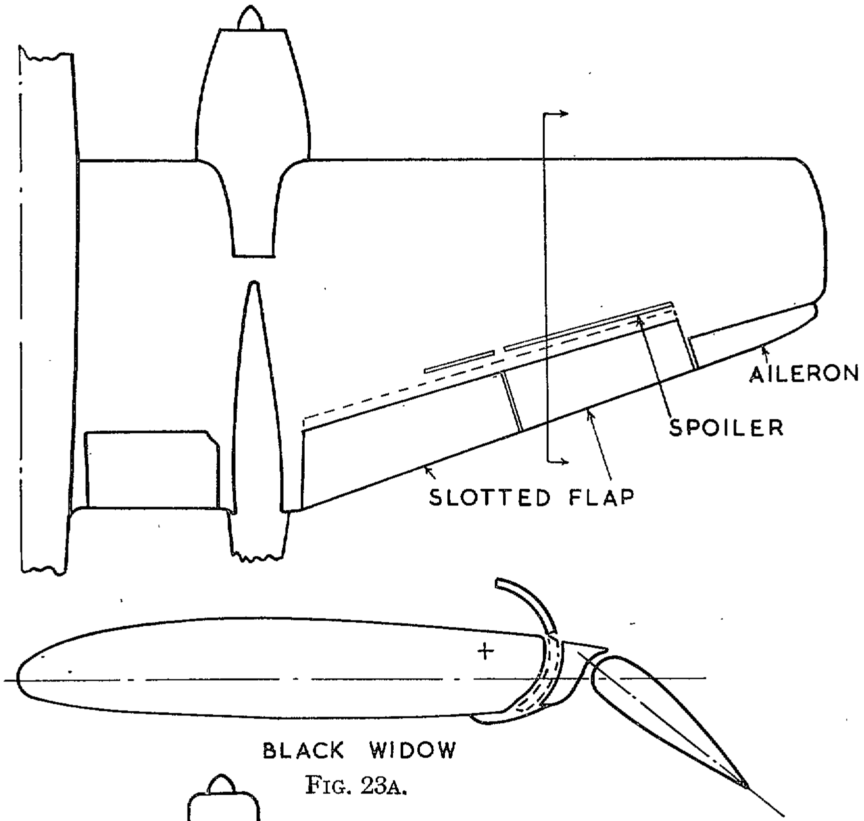
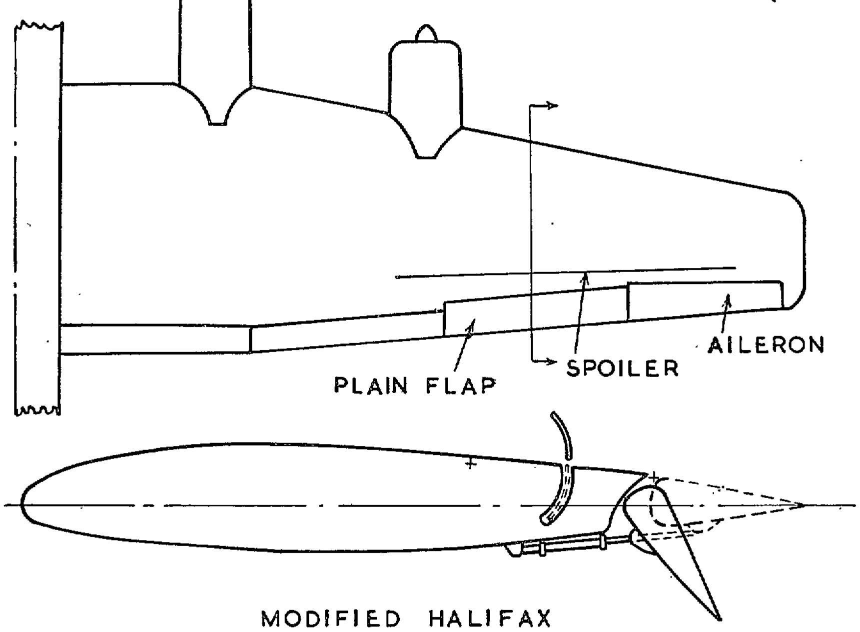


FIG. 22. Inset Aileron on Youngman-Baynes Aircraft.



BLACK WIDOW

FIG. 23A.



MODIFIED HALIFAX

FIG. 23B.

Retractable-arc Spoilers with Short-span Ailerons.

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