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Summary.—Reasons for Enquiry.—The following investigation formed part of a more general research on problems associated with high-lift flaps. To obtain the maximum advantage from such devices, a satisfactory alternative to the conventional aileron is required, permitting the flap to extend over the full wing span. Spoilers meet this condition, but further development to improve their hinge moment and response characteristics was clearly necessary at the time. The present work was undertaken for this reason.

Range of Investigation.—The static rolling, yawing and hinge moments were examined on (1) a series of hinged-plate spoilers, (2) a series of circular-arc spoilers, particular attention being given to the development of satisfactory hinge-moment characteristics. Subsequently, the latter, which proved to be of considerably greater promise with respect to the above consideration, were investigated for response.

Conclusions.—For a spoiler of the type illustrated in Fig. 2b, the hinge moment is sensitive to the degree of bevel γ . By hinging the surface concerned, so that γ can vary with displacement of the spoiler, it is shown, by means of an example, that promising hinge-moment characteristics are obtainable with a quite simple link system for controlling the bevel angle in the necessary manner. The present experiments, however, are mainly of interest in emphasizing the value of this device as a very effective way in which the required hinge-moment characteristics can be approached, and are by no means an exhaustive survey of what may be achieved in this direction. From the dynamic experiments, it is concluded that a spoiler-aileron fitted to a wing with full-span flap of the dimensions considered in the present investigation will have a satisfactory response under high speed or cruising and climb conditions in flight, but may become deficient in this respect as the stall is approached. An intersurface slot behind the spoiler, when the latter has to be located so far from the trailing edge (at approximately 50 per cent. of the wing chord), proves to be essential both in promoting a satisfactory initial development of static rolling moment, and in preventing an inadequate response. The slot, however, if unsealed when the control is not in operation, introduces a drag increment which would be excessive for high performance.

Introduction.—The present investigation forms part of a broader research† in connection with aerodynamic problems relating to high lift devices. One section of the programme concerned dealt with the question of lateral controls for use with full-span flaps, and an account is here given of some experiments designed to study the properties of certain types of spoiler-aileron, with the aim of developing subsequently a suitable control of this nature.

As is well known, the spoiler-aileron has proved to be more complex in some respects than its conventional counterpart. This applies particularly to the response and hinge-moment characteristics with which earlier research has been primarily concerned. The response depends on (a) the lag, (b) the sluggishness of the control, and it will be as well at this stage to recall the definitions which have been attached to these descriptive terms.

* Blackburn Aircraft Report. W.T. 84/42 (revised).

† Undertaken between 1941 and 1945 on behalf of the then existing Ministry of Aircraft Production.

Lag is said to occur where there is a lack of positive rolling action immediately the aileron is deflected, and is defined as the time interval, from the instant when the control is set in motion, during which there is zero rolling moment, or possibly an adverse moment. From general considerations of the flow in an accelerated boundary layer¹, there is reason to think that this quantity is proportional to c/V , where c is the wing chord and V the speed of flight, and it now appears well-established that there is also an absolute limit, amounting to about 0.1 sec., below which the lag becomes imperceptible to the senses.

Sluggishness is a similar property to lag, and is measured as the time required for the normal rolling moment to develop from zero to its maximum, steady value appropriate to the given deflection of the control. This interval may also be expected to vary linearly with c/V . It is probable, however, that no definite limit, at which sluggishness becomes objectionable, can be formulated, since in practice it will be judged rather by the rate of roll of the aircraft, and is consequently a function of its inertial characteristics. It has been tentatively suggested, nevertheless, that the maximum rolling moment should be developed in the time taken to traverse a distance of from four to eight chord lengths.

There remains the problem of the hinge-moment characteristics, namely the problem, common in varying degree to all controls, of ensuring that the operating force shall be proportional, at least approximately, to the control movement, and increase with increase of speed to a limit which, in all normal circumstances, shall not become unmanageable.

At the time when the present work was undertaken, it appeared, from the available publications* on spoiler-aileron research, that the attempts to meet the essential control characteristics had not been entirely successful, and further, that ancillary devices introduced to overcome the defects of the aileron were of a somewhat 'ad hoc' character and usually complicated aerodynamically. It will be generally agreed, however, that any such expedient, to be of practical value, should be not only simple and reliable mechanically, but should function aerodynamically in accordance with well defined principles which are not critically dependent on either Reynolds number, the geometry of the type of spoiler-aileron to be treated, the location of the aileron on the wing, or the characteristics of the wing itself, such as the plan form, section profile, arrangement of flaps.

The investigation described here may be said to constitute a further attempt to develop, by more systematic experiments, a satisfactory spoiler-aileron which conforms in so far as its composition is concerned, to the foregoing considerations, and, at the same time, satisfies the necessary control requirements referred to earlier.

2. *Types of Spoiler-Aileron Considered, and Wing-Aileron Arrangement.*—2.1. *Double, Hinged Plate Spoiler.*—In the initial stages of the investigation, a double, hinged plate spoiler, illustrated in Fig. 1 was considered. There were two reasons for selecting such an arrangement. First, the semi-wing (see Section 2.3), upon which the various spoiler-ailerons were examined, was fitted with a full-span, high-lift flap of chord approximately equal to half the wing chord. Hence, the spoilers could not be placed sufficiently near the trailing edge to be free, of themselves, from excessive lag. Accordingly, it was decided to fit an intersurface wing slot immediately behind the spoiler, an established and effective procedure^{2,3} for reducing lag. At the same time, it is known that such slots introduce an appreciable drag increment if unsealed, so that a spoiler arrangement such as that concerned may be conveniently employed to close the openings on both wing surfaces when the control is not in operation. Secondly, it was thought that the coupling of the hinged plates offered encouraging prospects of balancing the individual hinge moments to give a resultant of suitable magnitude and distribution. Several variants of the scheme illustrated in Fig. 1 were investigated, with essentially the same geometrical characteristics, *i.e.*, an upper surface plate hinged near its leading edge coupled by a single link to an under surface plate hinged in the vicinity of its trailing edge.

* Subsequently it was learned that contemporary experiments on similar lines to those described in this paper (see Section 4.1) had been performed independently in America by the N.A.C.A.

2.2. *Circular Arc, Retractable Spoiler.*—Two arrangements of this type of spoiler, illustrated in Figs. 2(a), 2(b), were considered. That of 2(a) will be recognised as the thin plate, retractable spoiler. The hinge coincided with the centre of curvature of the plate, and an inter-surface slot was incorporated for the reason given in (2.1). The spoiler of Fig. 2(b) only differed from 2(a) in that it had an appreciable thickness, the upper face being inclined or bevelled. Both types of circular-arc spoiler were placed in the same wing recess, to which a small cover plate, as shown in Fig 2a, was fitted in the case of the plate spoiler to form a narrow opening, or slit, with a working clearance for the spoiler of the same order as that provided in the alternative scheme.

2.3. *Wing-Aileron Model.*—The controls described in (2.1), (2.2) were installed on a rectangular wing of span equivalent to 102 in.* and chord of 16 in. The aerofoil section was that investigated in Ref. 4, and designated B.A.0018/12, *i.e.*, the section formed of NACA 0018 ordinates for the upper surface profile, and NACA 0012 ordinates for the lower surface profile. The flap, referred to as A in the above paper, was also fitted. This flap has a chord equal to half the wing chord, and an optimum angular displacement of approximately 50 deg., when it would appear to give about as large a lift increment as any single-slotted flap for which data have been published. It extended from the inboard end of the half wing out to a section 93 per cent of the model span from the centre line, the remaining 7 per cent of the span representing a tapered and rounded wing tip.

The spoiler-ailerons were all of equal length, namely 0.313 of the model span, and were located with the outboard end coincident with the corresponding end of the flap. Their dimensions and position in the chordwise direction are given in Figs. 1, 2.

3. *Nature of the Experiments and Description of the Apparatus.*—3.1. *Static Experiments.*—It was decided during the preliminary stages, when the experiments were still being planned, to deal first with the static conditions in an attempt to develop an aileron with satisfactory rolling, yawing and hinge-moment characteristics, and subsequently, to investigate any control of sufficient promise in regard to these requirements from the point of view of the dynamic properties discussed in Section 1. We shall therefore consider the work in the above order.

All the observations relating to both the static and dynamic experiments were made in the 7×5 ft. wind tunnel described in Ref. 5 at a Reynolds number, based on the wing chord, of $0.67.10^6$ †. For the measurement of rolling and yawing moments, the model, which represented the starboard half of the wing, was placed horizontally in the working section with the inboard end hinged to the tunnel wall, so that it remained free in roll and yaw, but constrained in pitch. At the opposite end, a steel rod, 3 in. long and $\frac{3}{8}$ in. in diameter, projected from the wing tip in a spanwise direction, and was connected to one of the vertical arms of the three-component roof balance (also described in Ref. 5), the second arm being removed. Thus, in terms of balance readings, the rolling moment was measured as a lift force acting on a lever arm equal to the spanwise distance between the wall-hinge axis and the centre of the balance arm attachment, whilst the yawing moment was determinable from the drag force acting at the same leverage. It follows that the rolling and yawing moments are referred to wind axes. Provision was also made for adjusting the incidence, the model rotating on its supports about a spanwise axis coincident with the quarter-chord point.

For the recording of aileron hinge moments, a single force, electrical balance, of the type described in Ref. 5, was mounted in a recess on the under surface of the wing, the opening being covered by a plate curved to the profile. The balance spring connected to one arm of a simple bell-crank lever pivoted about the aileron hinge centre, the other arm of the crank being bolted to a quadrant plate integral with the inner end of the spoiler. This quadrant plate contained a

* It will be clear from Section 3.1 that the model was confined to the half wing with the inboard end adjacent to one of the wind-tunnel walls. This, accordingly, acted as the plane of symmetry which occurs approximately at the median section of a wing of finite aspect ratio.

† The drag experiments discussed in Section 3.3 were an exception in that they were performed at a variety of wind speeds.

series of equally spaced, circumferentially disposed holes which engaged in turn with the bolt hole on the bell-crank, thus providing a means of varying the control angle by prescribed increments. The increment normally amounted to 5 deg., but was reduced to half this value, by drilling extra holes as required, when the conditions indicated that it was desirable. All the spoilers were mounted on high-grade ball bearings, carefully selected to ensure the maximum freedom from friction. In this manner the rolling, yawing and hinge moments were measured at control angles covering the full range, as indicated in Figs. 1, 2, for the two flap angles of $\beta = 0$ deg. (flap retracted) and $\beta = 50$ deg. (optimum flap position for maximum lift increment) at the following uncorrected angles of incidence*: $\beta = 0$ deg., $\alpha = 0$ deg., 5 deg., 10 deg., 15 deg.; $\beta = 50$ deg., $\alpha = -5$ deg., 0 deg., 5 deg., 10 deg. In the case of the spoiler (Fig. 2b), values of γ equal to 0 deg., -21 deg., -31.5 deg. and -40 deg., were also investigated.

3.2. *Dynamic Experiments.*—The method of recording the motion of the wing in roll due to a displacement of the control is illustrated in Fig. 3. The model was mounted in a similar manner to that of Section 3.1, except that the wall hinge was replaced by one permitting only freedom in roll about the wind axis, whilst the balance arm supporting the wing tip was removed, and a continuous, vertical, steel wire substituted. This wire was clamped to the wing tip attachment referred to in Section 3.1, and ran, through slots in the floor and roof of the tunnel, over adjacent, external pulleys P, as indicated in the diagram. The free ends of the wire were then carried horizontally above and below the working section to two winches W, lengths of suitably stiff shock-absorber chord being inserted in both of these sections of the cable, thus permitting the model to execute oscillations in roll. The wall hinge was also designed so that the wing could be set at any of the above angles of incidence, namely -5 deg., 0 deg., 5 deg., 10 deg., 15 deg., the roll axis being always coincident with the wind direction.

To analyse the motion in roll, it is sufficient to time the displacement of the wing tip. For this purpose, a source of light S_1 , consisting of a 4-V lamp, was placed in a recess on the wing tip, the recess being covered by a plate with a $\frac{5}{8}$ in. diameter aperture in it. The trace of this light-source was then recorded by means of a ciné camera C_1 placed with its optical axis parallel to the wing span in a convenient position outside the window of the tunnel door.

For an accurate measure of the time lapse, a second source of light S_2 (carbon arc) was located on the far side of the working section and focussed on a plane, steel mirror M cemented to the upper prong of a continuously excited tuning fork F which was arranged to vibrate in the vertical plane. A lens L and a small opening in the tunnel wall then brought the reflected ray to a focus at the wing tip. Finally, to give a time signal, an aperture A, of 0.03-in. diameter, was placed between the tuning fork and the tunnel wall such that the light was intercepted except when the fork was in the position of rest. In this manner, two signals per cycle, in the form of very fine points of light, were recorded on the film.

With regard to the automatic operation of the aileron (as will be seen later, only the circular-arc type spoiler was selected for the dynamic experiments), a spring was fitted to give a negative hinge moment, the spoiler being retained in the closed position against this moment by a plunger engaging with a shoulder on the spoiler quadrant. To release the aileron, a Bowden cable and spring were fitted to the plunger, the cable running in a conduit in the wing to an opening in the tunnel wall at the wing root, and thence to a point convenient for operation. In addition, the following device was fitted to control the displacement of the spoiler. Adjacent to the spoiler quadrant, a second quadrant, integral with the wing, was arranged, the two surfaces being

* *i.e.*, simply the geometrical values, as read on the telescopic protractor, under 'wind-on' conditions. Since the incidence correction is uncertain, however, it was thought preferable, in presenting the results, to employ the more reliable, though approximate, lift coefficients ($\xi = 0$ deg.) obtained from the rolling-moment data, on the assumption that the centre of lift occurs at 0.45 of the semi-span outboard from the rolling axis.

† The camera was a standard product, operating on 35mm. film, with a clockwork drive. Before using it for the immediate purpose, however, the necessary modifications were made to give a continuous film feed, the most convenient rate proving to be about 30 ft./min. in conjunction with a fork frequency of 50 c/sec. A complete record of the essential features of the motion following a sudden displacement of the control was then given in a film length of 10 to 15 in.

parallel to one another with no more than a working clearance between them. In this case, the spoiler quadrant contained only one hole set accurately at the same radius as three holes of the same diameter in the wing quadrant, the latter being disposed circumferentially to correspond to spoiler displacements $\xi = -15$ deg., -30 deg., -45 deg. (maximum angular movement). A short pin could be inserted in these holes until it made contact with the surface of the spoiler quadrant, and was retained in this position by a light axial pressure from a leaf spring resting on the opposite end of the pin. Hence, by inserting the pin into one of the above wing-quadrant holes, the spoiler, on being released, was subsequently arrested by the pin engaging, under the spring pressure, with the hole in the spoiler quadrant immediately the latter had moved into coincidence with the pin.

The timing of the spoiler displacement, controlled by this very simple and reliable device, was obtained from a 4-V lamp S_3 , mounted on the upper surface of the wing adjacent to a shutter interposed between the lamp and the camera. This shutter was attached to the spoiler, and contained apertures so arranged that light from S_3 to the camera was intercepted whilst the spoiler was in motion, but gave a continuous trace when it was at rest. The time taken by the spoiler to attain a given displacement was accordingly calculable from the intervals thus recorded on the film. For the reason given below, no provision was made to restore the control automatically to the neutral position, *i.e.*, the mechanism was not reversible, the latter operation being performed manually on the model.

Concerning technique, the wing was first adjusted on the wing-tip clamp so that for wind-on conditions the wing floated with slight positive dihedral. The winches were then adjusted until, on releasing the aileron, the wing deflected to a steady position roughly the reflection of the initial position. Several rubber cable combinations were also necessary to ensure that the wing-tip displacement was of the permissible order, about 6 in. maximum, under all experimental conditions. Only observations of the response characteristics for negative control movements (deflection from the neutral position) were made because the evidence of Refs. 3 and 6 shows that the response for deflections in the opposite sense, *i.e.*, when the control is returned to the neutral position, is generally better. The relevant records of Section 4.2 also represent the mean of the observations of three consecutive experiments under each set of initial conditions, since it was found, no doubt due to the sudden disturbance and subsequent temporary irregularity of the flow over the upper surface*, that repetitions of an experiment were liable to show measurable, but apparently random, local variations in the time-displacement curves. It is considered, however, that the average data give a reliable representation of the more stable elements of the motion. Only the spoiler of Fig. 2b with $\gamma = -31.5$ deg. was considered dynamically, observations being made for deflections of the control amounting to -15 deg. and -45 deg. at both flap angles, *i.e.*, $\beta = 0$ deg. and $\beta = 50$ deg.

3.3. Subsidiary Experiments.—In addition to the experiments described above, some observations were made of the effect of the inter-surface slot on (a) the growth of static rolling moment for small control movements, (b) the drag of the wing, (c) the response. To analyse the response characteristics fully, it was also necessary to measure the damping in roll.

As regards (a), only the circular-arc plate spoiler and the related spoiler ($\gamma = -40$ deg.) were investigated for small control angles (0 deg. $< \xi < 20$ deg.) .The effect of the flap was also included.

The drag (b) was measured first with the slot open, and afterwards with a plasticine seal, which was carefully shaped to the wing profile. Throughout the experiment the spoiler was retained in the neutral position, and several values of the lift coefficient in the range $0 < C_L < 0.7$ (flap retracted) were considered. To measure the drag, the model was suspended from the tunnel balance in the normal manner, except that the wing was offset with no more than a working clearance between the inboard end and the one wall of the tunnel. The drag set up by this gap

* Similar experience with regard to the unsteadiness of the motion is reported in Ref. 6.

and the interference between the wing and the wall were of no consequence, since only drag increments due to the flow through the slot were considered. Full-span, turbulence wires, of 0.011-in. diameter, were also attached to the upper and lower surfaces at a section 4 per cent. of the chord from the leading edge. In this manner the drag increment was obtained at several wind speeds covering the range of Reynolds number $0.5 \cdot 10^6 < Vc/\nu < 1.36 \cdot 10^6$.

The effect of the slot on response (c) was confined to the circular arc spoiler ($\gamma = -31.5$ deg.). Observations were made over the incidence range for both flap positions, namely $\beta = 0$ deg., $\beta = 50$ deg., but the control movement was restricted to $\xi = -15$ deg., since it was found that the response was less satisfactory for a small control movement than for a large one.

Finally, the damping in roll was measured by the method of forced oscillations. For this purpose, a light vertical rod was connected to the under surface of the wing at a short distance from the tip. This rod passed through an opening in the floor, and was connected at the lower end to a suitable spring actuated by the usual motor and eccentric. The elastic suspension of the model differed in no respect from that adopted for the response experiments, and the resonance conditions were conveniently recorded by the camera and timing system described in Section 3.2.

4. Discussion of the Results.—4.1. Static Characteristics of the Aileron with the Intersurface Slot Open.—(a) Hinge moment.—The experiments on the plate spoiler (Fig. 1) were discouraging on account of the difficulties encountered with respect to the hinge-moment characteristics. In all, seven arrangements were investigated, the main variable being the size of the lower-surface plate. This ranged in width from about 20 per cent. of the wing chord in the first instance to between 6 per cent. and 7 per cent. of the chord in the final and most satisfactory combination investigated (see Fig. 1). Other minor variations of geometry were also present in the different schemes, but in every case the distribution of the hinge-moment coefficient C_h proved to be critical as the control first came into action, the moment being either very irregular, *i.e.*, of an oscillatory character with respect to the displacement ξ , or else exhibiting a comparatively rapid increase of moment initially, followed by a gradual decrease, as instanced in Fig. 4. This undesirable feature would appear to be a fundamental property of such an arrangement, and, although no direct evidence was obtained to support the view, is very probably associated with an early stall of the lower plate.

Accordingly, the development of the hinged-plate spoiler was abandoned in favour of the circular-arc type, illustrated in Fig. 2(b). This spoiler is also prone to rather rapid changes of C_h , either positively or negatively, during the initial stage of operation, followed by an appreciable range of ξ (negative) in which C_h is virtually constant, and finally, as the control approaches its maximum displacement, by an increase of the coefficient in the positive sense*. At the same time, the angle γ of the upper face of the spoiler has a pronounced influence on the magnitude of C_h . This feature is clearly exhibited in Figs. 5 and 6, from which it will be observed that, for negative values of ξ , C_h is very nearly a linear function of γ in the approximate range 0 deg. $< \gamma < -35$ deg., a maximum occurring in all circumstances at $\gamma \approx -35$ deg. Beyond $\gamma = -40$ deg., the curves are indefinite, since no experiments were made for larger values of γ , but the value of C_h at $\gamma = -90$ deg. is clearly equivalent to that of the indefinitely thin circular-arc spoiler, to which the arrangement shown in Fig. 2a approximates. The curves of Figs. 5, and 6 have, therefore, been completed by taking the values of C_h measured on this spoiler as applicable when $\gamma = -90$ deg.

After the work of the present investigation had been completed, it was learned that experiments⁸ on a similar device for controlling the hinge-moment characteristics of a spoiler aileron had been performed in America. As will be seen from Ref. 8, the spoiler concerned resembles that

* The rapid development of a negative moment, which occurs mainly with the unbevelled spoiler ($\gamma = 0$ deg.) over a small interval of ξ as the control is displaced initially, would appear to be evidence in support of the 'snatch' experienced in flight with a similar type of spoiler (see R. & M. 25837, Section 3.14). The form of the C_h , ξ curves ($\gamma = \text{constant}$), as here described, may be readily verified from cross-plots of Figs. 5 and 6.

considered here, although there are a number of differing features, notably the provision of vents. Nevertheless, analysis of the hinge-moment coefficient as a function of γ from the data provided in Figs. 10a, 10b of the report in question yields results in general accord with those indicated in Figs. 5, 6 above. As in the present experiments, when the control is deflected negatively, C_h increases initially to a maximum and tends to zero as γ approaches -90 deg. For positive values of ξ , there is also general agreement, *i.e.*, the coefficient is relatively quite small and practically independent of γ . The main properties of the movable plate as a means of adjusting the hinge moment appear, therefore, to have been fairly well defined.

By the incorporation of a suitable mechanism to give the appropriate variation of γ with ξ , it follows theoretically that any desired hinge-moment characteristics may be imparted to the control. On the evidence of the present data, however, it would appear, as we shall see below, that the ideal condition of a linear variation of moment with aileron displacement at a constant speed of flight is not attainable without an excessively complicated system of operation. Moderately satisfactory results are possible, on the other hand, by quite simple means.

An example of such a scheme is illustrated in Fig. 7, wherein the spoiler is hinged at O, and the movable plate CD at C, whilst DE is a link of fixed length pinned at D and E, the co-ordinates of E with respect to O parallel and normal to the wing chord, let us say, being \bar{x} , \bar{y} . It is also sufficient and convenient to represent the control circuit in the rudimentary form portrayed in the diagram, which gives simply*

$$\sin \xi \simeq k \sin \delta$$

for the relation between the control lever and aileron displacements, where k is an arbitrary constant.† Hence, assuming there is no differential action, and taking the response factor as unity for a spoiler-aileron,

$$\frac{2Fl}{\rho V^2 S_\xi c_\xi} = \Delta C_h \frac{d\xi}{d\delta} = k \Delta C_h \frac{\cos \delta}{\cos \xi} = f(\delta), \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (1)$$

in which ΔC_h denotes the difference of C_h from the two ailerons.

For various combinations of \bar{x} , \bar{y} , widely differing curves of the moment coefficient to operate the control (Eqn. 1) as a function of δ are obtained. Figs. 8 and 9 represent, it would seem, about the best conditions possible with such a simple scheme, based, of course, on the aerodynamic results here considered. It will be noted that the moment curves are consistently characterised by waves which may or may not be of sufficient magnitude to be felt in practice. The elimination of any one wave is easily accomplished by a re-choice of \bar{x} , \bar{y} , but in this case a new wave invariably appears at another part of the curve, so that to remove all irregularities simultaneously, even if it is possible, must clearly involve an unwarrantably complex mechanism for setting CD. In the example presented, the force required to operate the control under modern conditions of high-speed flight, in instances where spoilers might be preferable to conventional ailerons, is also unduly large, but this defect may be removed by reducing the thickness of the spoiler, for ultimately, in the case of the indefinitely thin circular-arc spoiler, the hinge moment becomes vanishingly small in all circumstances. Thus, the hinged plate provides a means of controlling both the magnitude of the force to operate the aileron and its rate of development. From a study of the curves in Figs. 5 and 6, it will be readily appreciated, however, that this device is very sensitive to the setting γ , so that any departure from the prescribed value, due to backlash or lack of stiffness of the spoiler, for example, may produce very serious disturbances of the intended operating characteristics.

Finally, it will be noted that the moment coefficient (Eqn. 1) decreases with increase of lift coefficient for both flap conditions ($\beta = 0$ deg., 50 deg.) and, when the flap is retracted, is liable to result in overbalance for small movements of the control as the stall is approached.

* The length of the link AB is taken to be of the order of the wing semi-span.

† In the calculations referred to below, k was chosen so that $\delta_{\max} = 20$ deg.

(b) *Rolling and yawing moments.*—The rolling and yawing-moment curves (see Figs. 4, 10, 11) for both the hinged-plate and circular-arc types of spoiler exhibit the typical features observed in previous investigations of a similar nature. It will be noted that, with the flap retracted, the rolling moment increases fairly evenly with control movement, whereas, when the flap is lowered the generation of rolling moment is rather weak initially, followed by a very vigorous development up to about half the maximum control angle. The rate of increase is then much reduced again. This suggests that slotted flaps, when used to their maximum effect, may make the rolling characteristics somewhat irregular, particularly for small control movements about the neutral position. In this respect the present data indicate that the circular-arc plate spoiler is somewhat superior to the other two arrangements. The effect of the bevel on the rolling and yawing moments proved to be trifling, and for this reason only one typical case ($\gamma = -31.5$ deg.) has been illustrated.

As regards the adequacy of the rolling moments developed, if we accept the criterion advanced in Ref. 9 that $\phi b/2V$ in the steady state should not in general be less than 0.07, we obtain from Ref. 10, Eqn. (b) a value of C_l' equal to 0.035. Thus, all the spoilers meet this condition at the maximum control angle when the flap is retracted, and with a very substantial margin when it is lowered.

4.2. *Response Characteristics of the Aileron.—Intersurface Slot Open.*—In terms of the notation on page 10, the equation defining the development of rolling moment with time, following an application of the control under the conditions described in Section 3.2, is

$$L' = A\ddot{\phi} + (\mu + \mu_1)\dot{\phi} + k\phi \quad \dots \quad (2)$$

As stated in Section 3.3, the damping coefficients μ , μ_1 were measured by the method of forced oscillations, the value of μ , which is equal to $-l_p$, proving to lie between 0.40 and 0.43 over the range of C_L considered, namely $0 < C_L < 1.1$, $\beta = 0$ deg. and $1.6 < C_L < 2.8$, $\beta = 50$ deg. The moment of inertia A was both calculated and measured, with satisfactory agreement, whilst the spring stiffness k was determined after each experiment in view of the somewhat unstable mechanical properties of rubber, and its susceptibility to 'ageing'. An attempt was also made to obtain the angular velocity and acceleration by analytical treatment of the data from the time-displacement records, but the labour involved for a satisfactory degree of accuracy proved to be prohibitive, and subsequently resort was made to successive graphical differentiation. For this purpose, the films were first enlarged to four times the original size. The results of the analysis for the conditions investigated (see Section 3.2) are presented in Fig. 12. The lag is very evident, particularly with the flap deflected, when the rolling moment appears to increase immediately at practically the maximum rate, in contrast to the more gradual development initially when the flap is retracted. By reference to Fig. 11, it will also be observed that the limiting value of the moment coefficient, when essentially steady conditions are established, agrees satisfactorily with the relevant static value after due allowance has been made for the secondary oscillations, attributable, it is thought, to flow disturbances set up by the spoiler.

From the above results the lag and sluggishness, expressed non-dimensionally as a measure of c/V , have been extracted, and plotted in Fig. 13. When the flap is retracted, the lag gradually diminishes with increase of incidence. This is to be expected, since the boundary layer becomes progressively less stable as the stall is approached, and hence the break down of the flow is more rapidly achieved by the spoiler at the higher lift coefficients. On the other hand, when the flap is deflected, it appears that the lag has a constant value about equal to that near the stall of the basic section, due, possibly, to less stable flow conditions generally when the flap is in action. By definition the sluggishness is measured as the interval in which the rolling moment develops from zero to its maximum value. As, however, the instant corresponding to the maximum is rather uncertain in practice, owing to the presence of the secondary oscillations already mentioned, it was decided to take the upper limit as the point at which the static rolling moment is attained. This, it will be noted, occurs somewhat before the maximum, apart from one or two instances near the stall, and hence provides, in all but these exceptional cases, a clearly defined interval

which may be regarded as a measure of the effective sluggishness. In contrast to the lag, the sluggishness increases rapidly when the stall is approached, either with or without the flap in operation, and is of about the same order in either case.

As regards the limits of wing chord and speed imposed by the desirable restrictions on lag and sluggishness under flight conditions, the data of Fig. 13 indicate that, if we take 0.1 sec. to be the maximum permissible lag, then c/V is equal to 0.083 sec. with the flap extended, as, for example, in the approach to a landing. Thus, when $V = 100$ ft./sec., the chord c is limited to 8.3 ft. The corresponding sluggishness is of the order of 0.8 sec., or about 9.6 chords, at the above speed. Provided the flap is not retracted, the indications are that c/V for the above maximum lag remains constant with increase of speed, so that the allowable chord is proportionately reduced, but that the sluggishness, in terms of a time lapse, may then be reduced up to a maximum of some 30 per cent. Measured as a space displacement, however, there may clearly be little or no improvement, since the smaller time interval is counterbalanced by the increase of speed. Conditions near the stall with the flap retracted are roughly the same as those prevailing when the flap is extended, *i.e.*, c/V of the order 0.08 sec. for 0.1 sec. lag, and a sluggishness of about 0.8 sec. Under high-speed conditions, it appears that, to satisfy the lag requirement, c/V need not be less than about 0.025 sec. if no more than 15 deg. of control angle are applied, or about 0.05 sec. for the full control movement. In point of fact, under modern conditions, c/V for a heavy transport aeroplane at maximum speed does not exceed 0.05 sec., and for a small high-performance type the corresponding figure is in the vicinity of 0.01 sec. Hence, for all designs other than one of exceptionally large size and comparatively low speed, the lag of the spoiler should be substantially less than the maximum allowable. The values of the sluggishness corresponding to the above extremes of c/V are respectively 0.3 sec., or 6 chords at about 450 ft./sec., and 0.06 sec., or again 6 chords at 1,000 ft./sec.

Without intending to press conclusions based on such limited data beyond justifiable limits, it would seem, nevertheless, that a wing with flap and spoiler arrangement similar to that investigated here will have negligible lag and probably acceptable sluggishness at the higher speeds, but that nearer the stall there are likely to be deficiencies with respect to both characteristics.

One final point which has a bearing on the above conclusions should perhaps be added, namely, the effect which the rate of operation of the control may have on the response characteristics. It will be noted from Fig. 12 that the deflection of the control was accomplished in a very much shorter time than can be achieved by hand, and consequently it is possible that the above conclusions may be somewhat too favourable in the case of manual operation. There appears to be no direct experimental evidence relating to this point, but some results in Ref. 3 (*see* Figs. 3 and 8) suggest that the lag, at any rate, is not materially affected for rates of deflection between one quarter and one tenth of the values in the present experiments.

4.3. Effect of the Intersurface Slot on the Static and Dynamic Characteristics of the Aileron.—The effect of the slot on static rolling moment is shown in Fig. 14. The data clearly indicate the deterioration which arises when this device is absent. Further evidence for the indispensability of a slot with very large chord flaps, apart, of course, from the split type, is to be found in Figs. 13 and 15. They amply demonstrate the considerable increase of lag to values which would be unacceptable in all circumstances except, possibly, for the small high-performance aeroplane in the region of maximum speed. The sluggishness, on the other hand, is appreciably reduced by eliminating the slot, but this does not necessarily indicate an improvement, for, coupled with the unusually large lag, it may lead to excessive control movement, followed by a sudden and objectionably vigorous rolling action.

In conclusion, as regards the drag increment produced by the slot (*see* Fig. 16), it appears that at maximum speed the increase of drag coefficient is likely to amount to about 8 per cent., and, under climbing conditions, to about 20 per cent. The present results are in very reasonable agreement with those of Ref. 3 obtained in flight on a Fairchild 22 aeroplane fitted with a 'slot-lip' aileron at 0.45 of the chord from the leading edge. It is therefore interesting to note that in this

instance the slot was estimated to reduce the maximum speed by 3.5 per cent., the optimum rate of climb by 13 per cent. and the maximum angle of climb by 10 per cent. Other experiments reported in the above reference show that the drag increment diminishes progressively with increasing rearward location of the slot and aileron, as is to be expected, but this fact does not offer a practical solution, since the main application of the spoiler-aileron is associated with the large-chord, high-lift flap. At the same time, the above figures indicate that an unsealed slot, when the control is not in action, would be unacceptable on a high-performance aeroplane. A possible solution with the present type of circular-arc spoiler and variable bevel would be to extend the movable plate in a rearward direction, so that it covered the upper-surface opening of the slot, and to eliminate any undesirable hinge moment thus introduced by appropriate modifications of the plate link mechanism.

Notation

The results of this report are stated for the starboard wing in terms of the notation at present adopted by the Aeronautical Research Council. Other symbols and definitions used are:

$$C'_l, C'_n = \frac{L', N'}{\frac{1}{2}\rho V^2 S b}, \text{ rolling, yawing-moment coefficients with respect to wind axes.}$$

$$C_h = \frac{H}{\frac{1}{2}\rho V^2 S_\xi c_\xi}, \text{ spoiler hinge-moment coefficient.}$$

c_ξ section of the chord aft of the hinge axis for the plate-type spoiler, or chord of the mean arc for the circular-arc type spoiler.

S_ξ area of the spoiler, given by the product of its span and the chord, as defined above.

β flap angle.

δ angular displacement of the control column.

γ bevel angle of the circular-arc spoiler, defined as in Fig. 2b.

A moment of inertia of the model about the wind-rolling axis.

μ aerodynamic damping coefficient in roll.

μ_1 corresponding frictional damping coefficient of the apparatus.

k spring stiffness constant.

N.B.—In estimating rolling and yawing-moment coefficients, the results have been taken to refer to the equivalent complete wing, *i.e.*, the coefficients are based on double the area and span of the model. This, consequently, implies that the rolling and yawing moments may be attributed exclusively to the half of the wing on which the spoiler acts, any associated changes of the forces on the other half being neglected.

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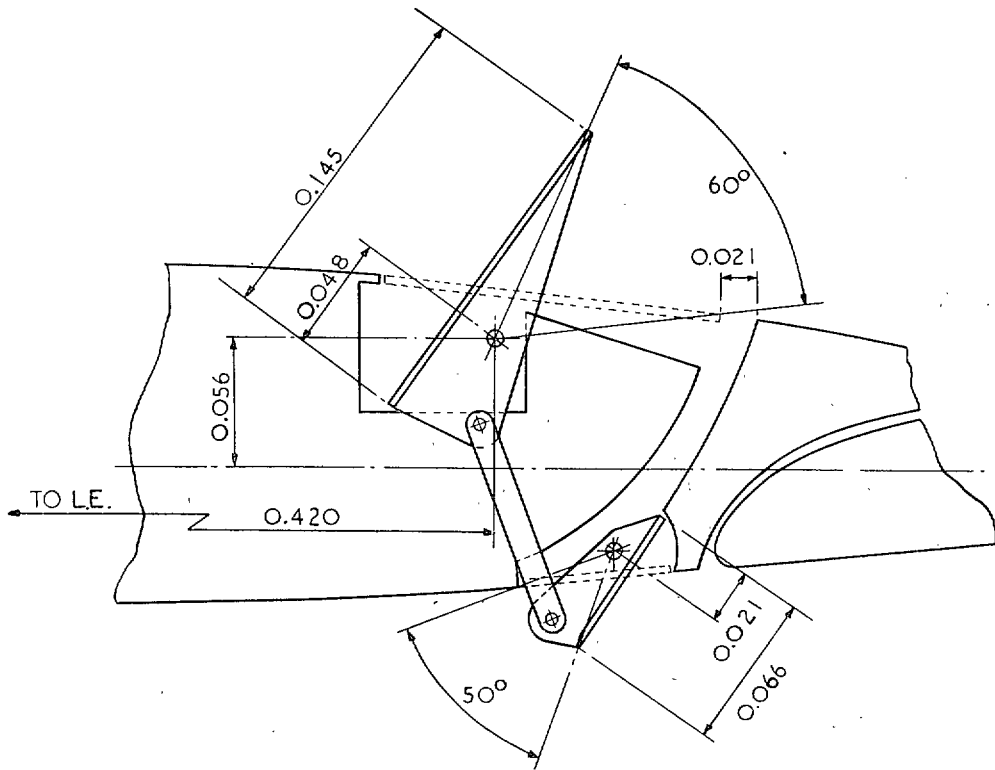


FIG. 1. Double Hinged-plate Spoiler. Dimensions Shown are in Terms of the Wing Chord.

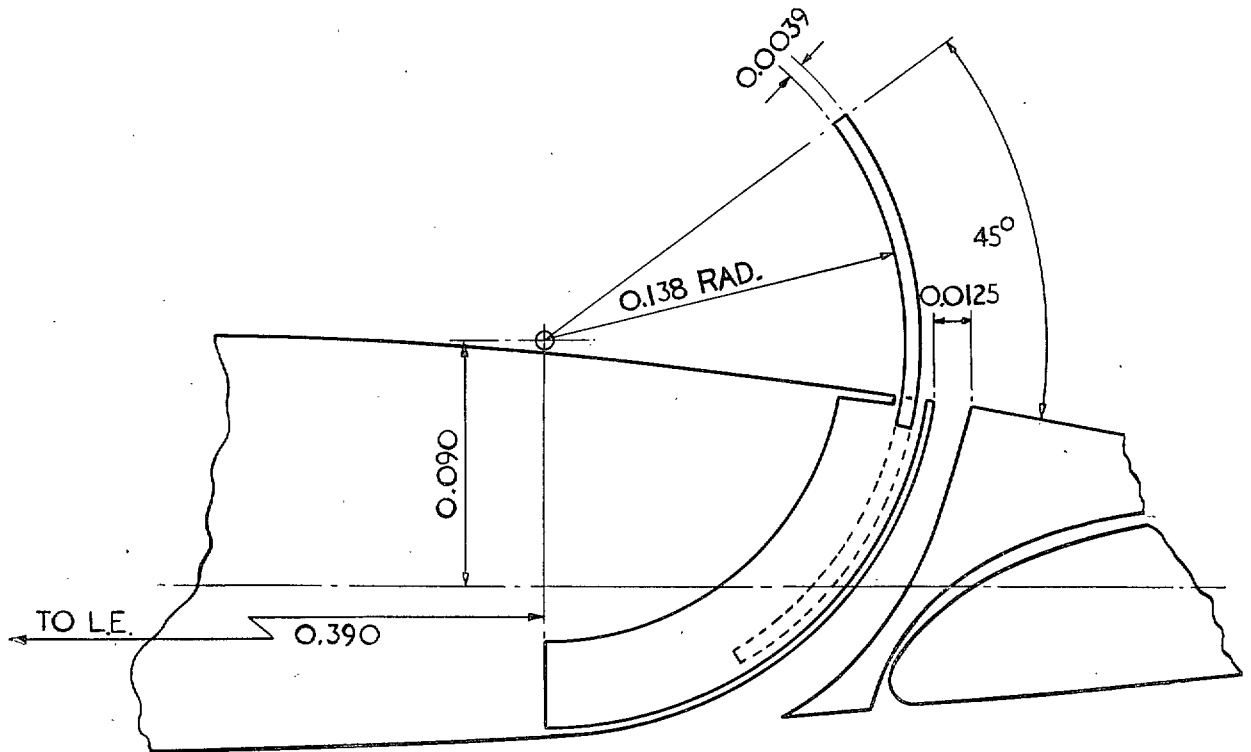


FIG. 2(a). Circular-arc Plate Spoiler. Dimensions Shown are in Terms of the Chord.

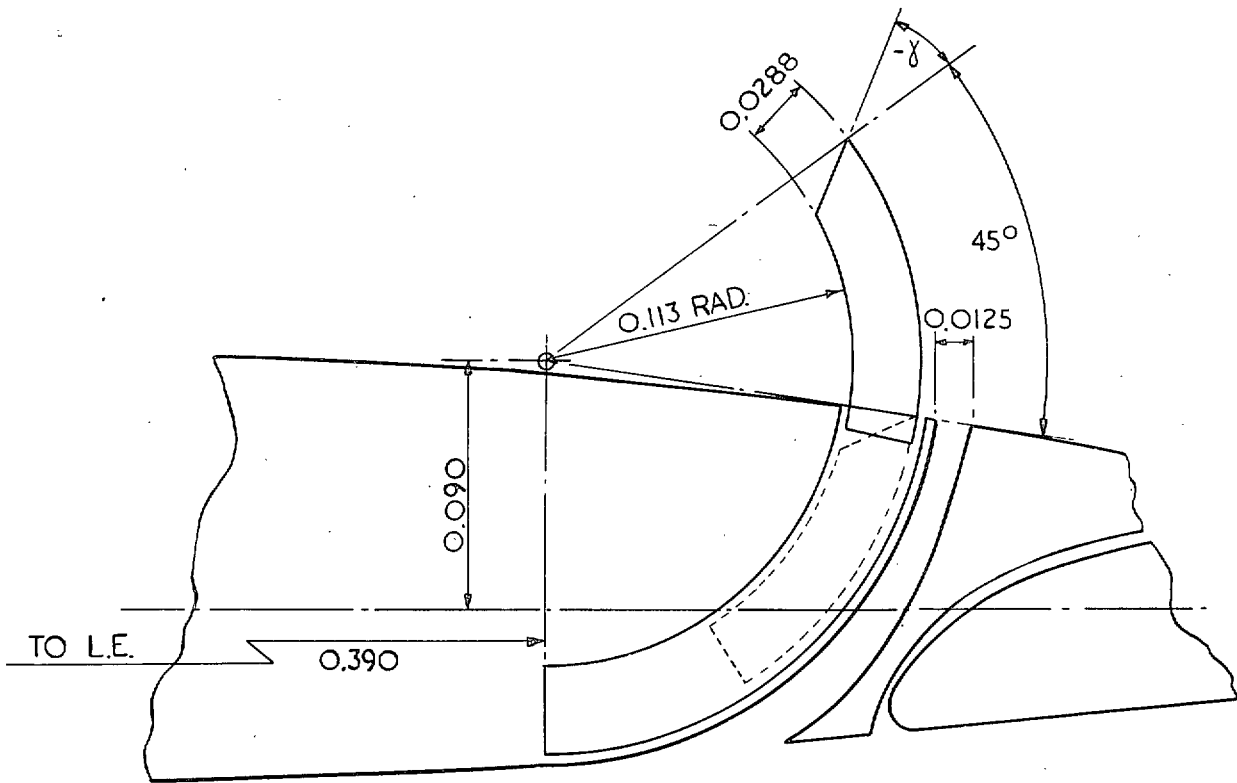


FIG. 2(b). Circular-arc Spoiler with Bevel. Dimensions Shown are in Terms of the Chord.

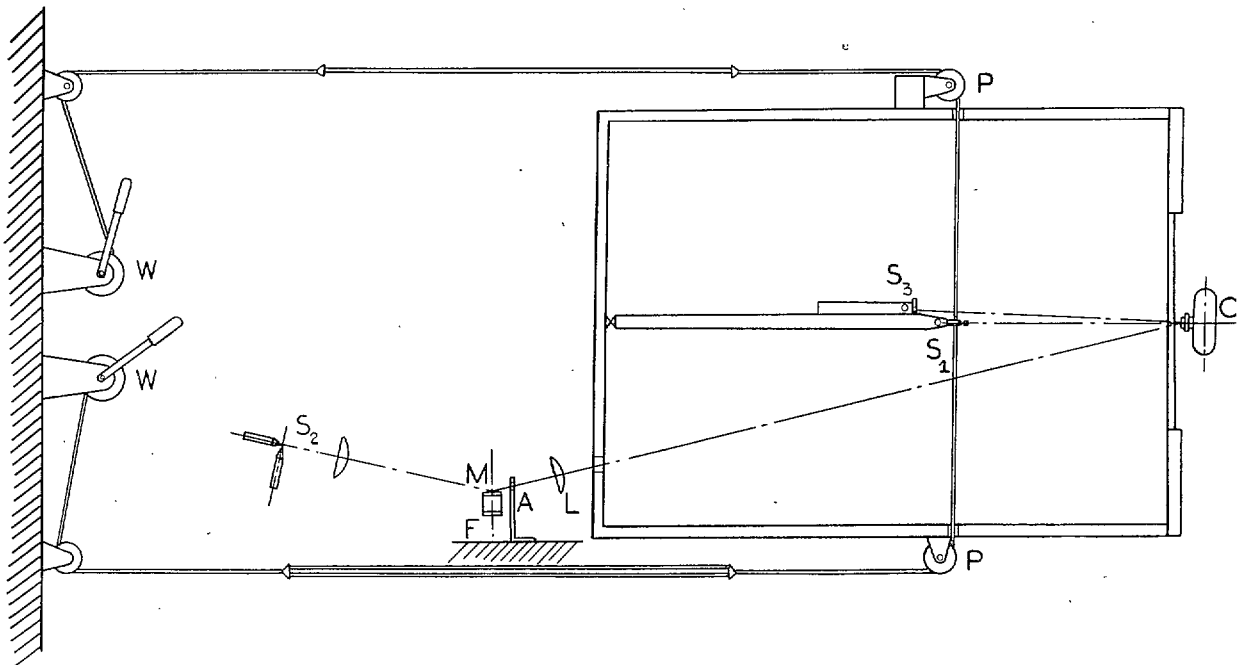


FIG. 3. Apparatus for Measuring the Response.

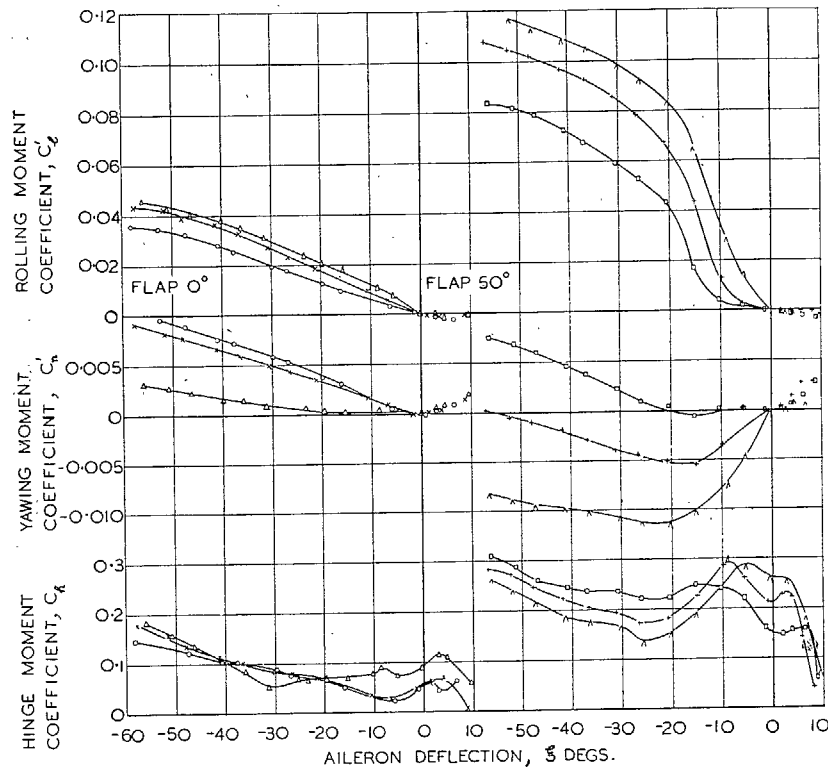


FIG. 4. Rolling, Yawing and Hinge-moment Coefficients of the Plate Spoiler (Fig. 1).
 ○ $C_L \approx 0.04$, × $C_L \approx 0.43$, △ $C_L \approx 1.12$,
 □ $C_L \approx 1.64$, + $C_L \approx 2.40$, ∧ $C_L \approx 2.83$.

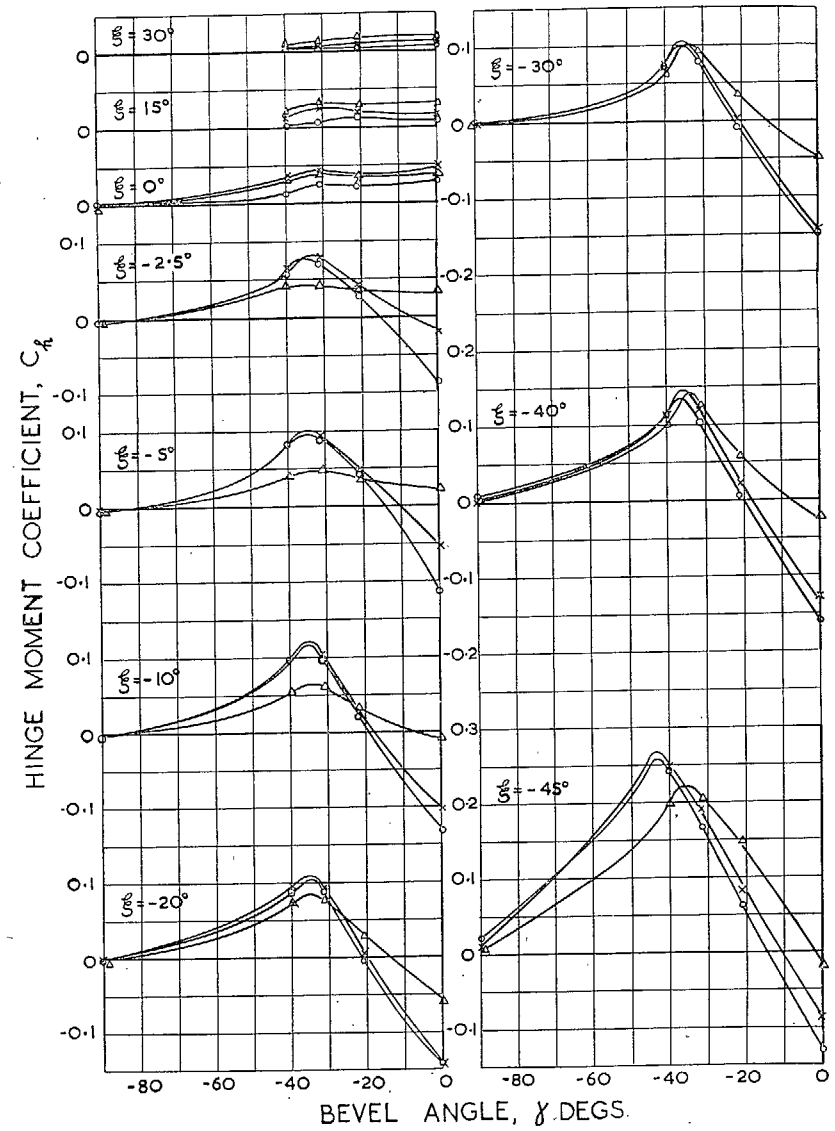


FIG. 5. Hinge-moment Coefficient as a Function of γ (see Fig. 2b).
 Flap 0 deg.
 ○ $C_L \approx 0.02$, × $C_L \approx 0.37$, △ $C_L \approx 1.03$.

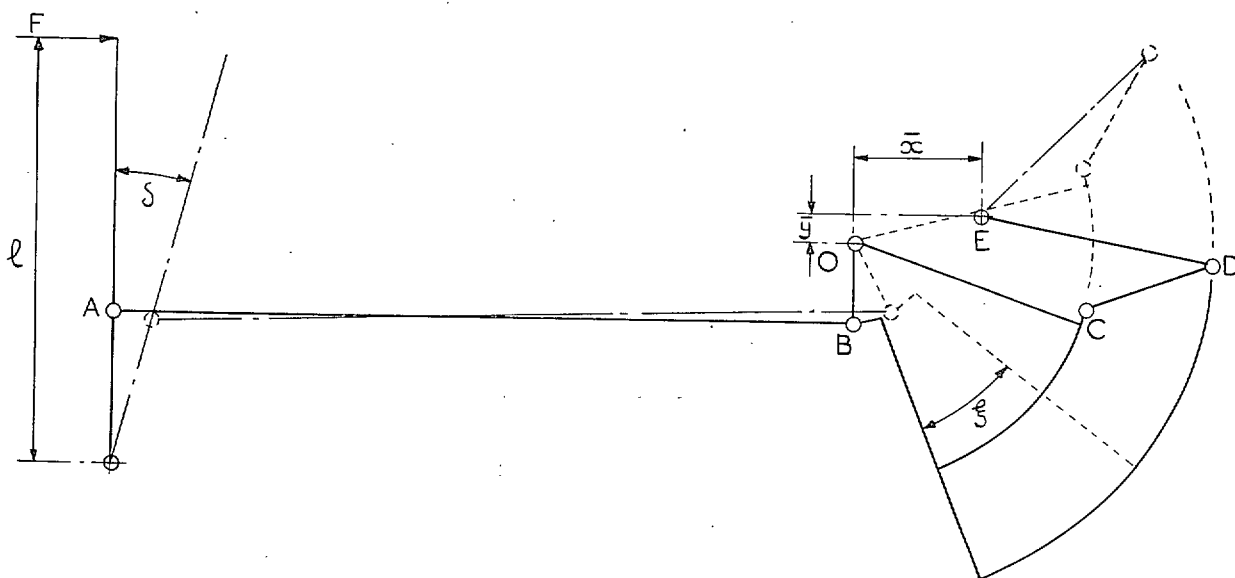


FIG. 7. Example of Spoiler-aileron with Movable Plate to Give Variable γ .

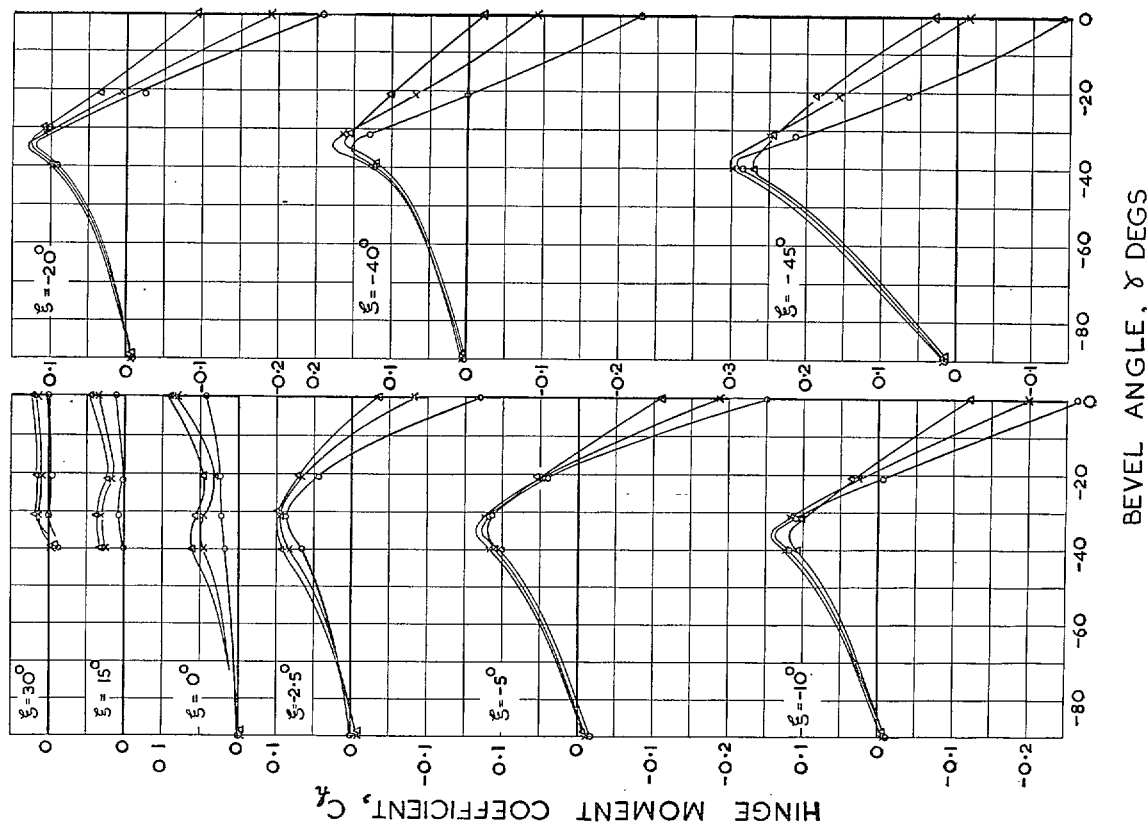


FIG. 6. Hinge-moment Coefficient as a Function of γ (see Fig. 2b).
Flap 50 deg.

○ $C_L \approx 1.67$, × $C_L \approx 2.37$, △ $C_L \approx 2.72$.

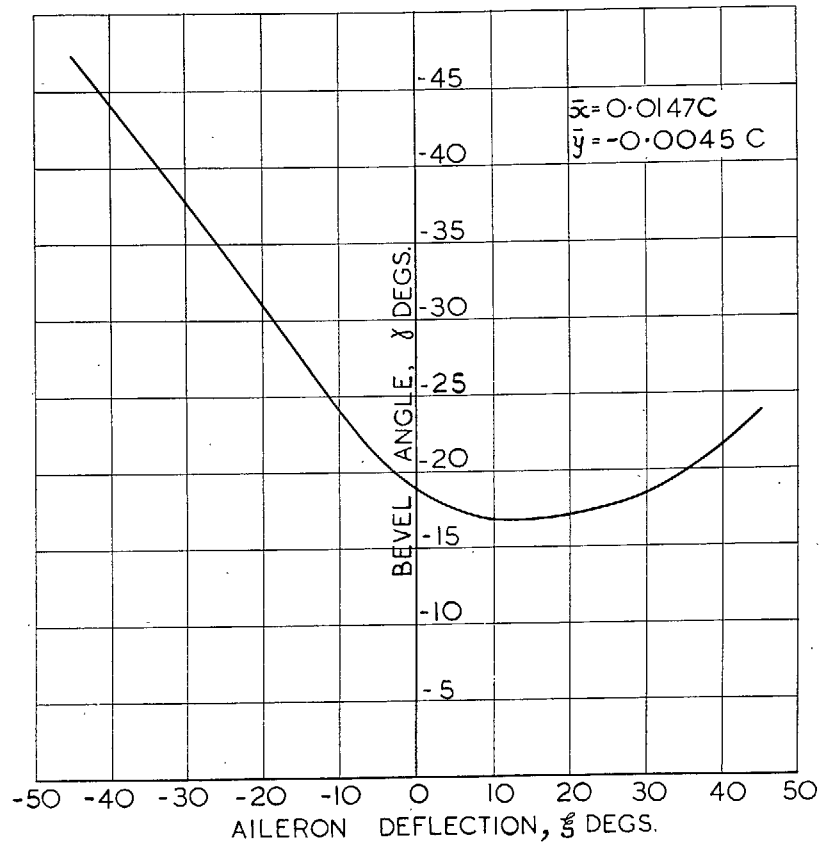


FIG. 8. Relation between γ and ξ for the Scheme shown in Fig. 7.

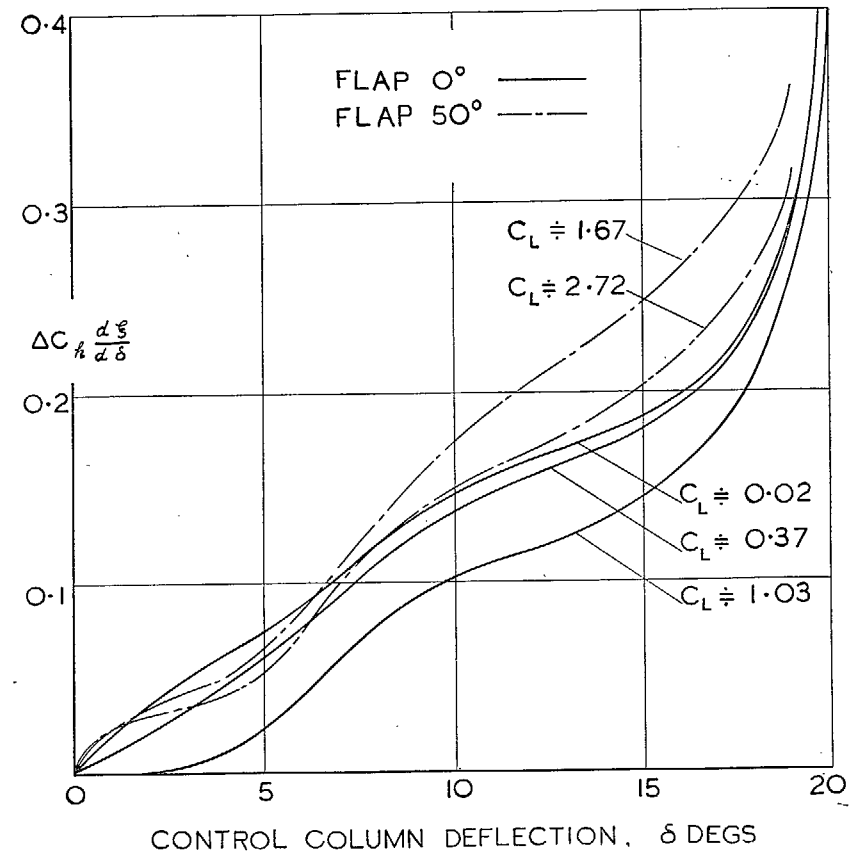


FIG. 9. Example of the Control-column, Hinge-moment Characteristics for the Spoiler-aileron with Movable Upper Plate.

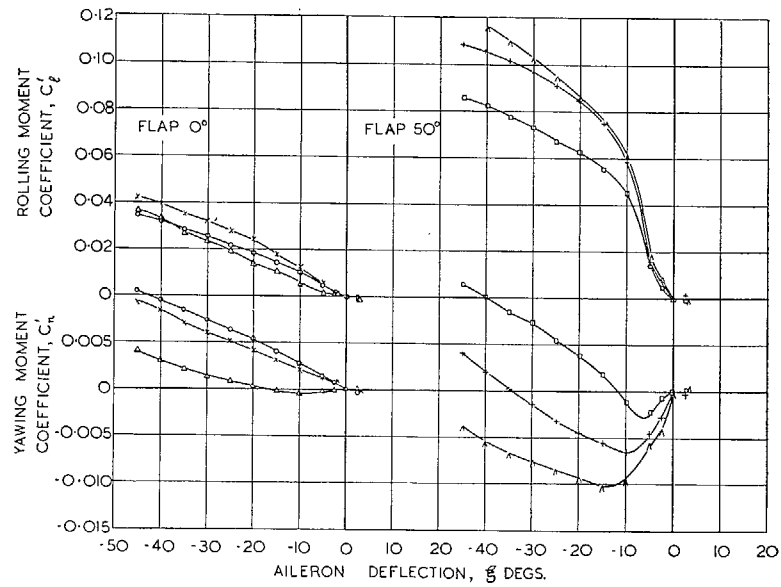


FIG. 10. Rolling and Yawing-moment Coefficients of the Circular-arc Plate Spoiler. (Fig. 2a).

○ $C_L \approx 0.03$, × $C_L \approx 0.39$, △ $C_L \approx 1.04$,
 □ $C_L \approx 1.89$, + $C_L \approx 2.40$, ∧ $C_L \approx 2.76$

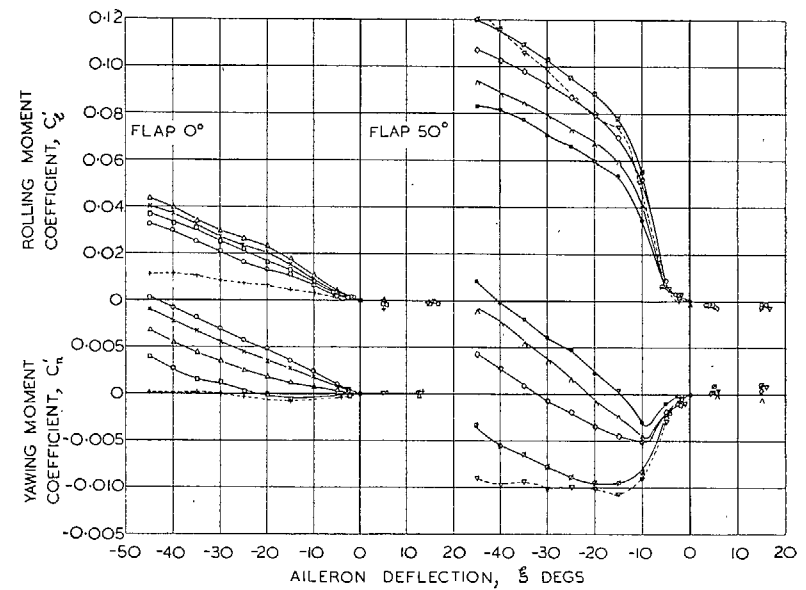


FIG. 11. Rolling and Yawing-moment Coefficients of the Circular-arc Spoiler (Fig. 2b). $\gamma = -31.5$ deg.

○ $C_L \approx 0.01$, × $C_L \approx 0.38$, △ $C_L \approx 0.74$,
 □ $C_L \approx 1.03$, + $C_L \approx 0.8$ (wing stalled),
 • $C_L \approx 1.67$, ∧ $C_L \approx 2.00$, ◇ $C_L \approx 2.36$,
 ∅ $C_L \approx 2.71$, ▽ $C_L \approx 2.8$ (wing stalled).

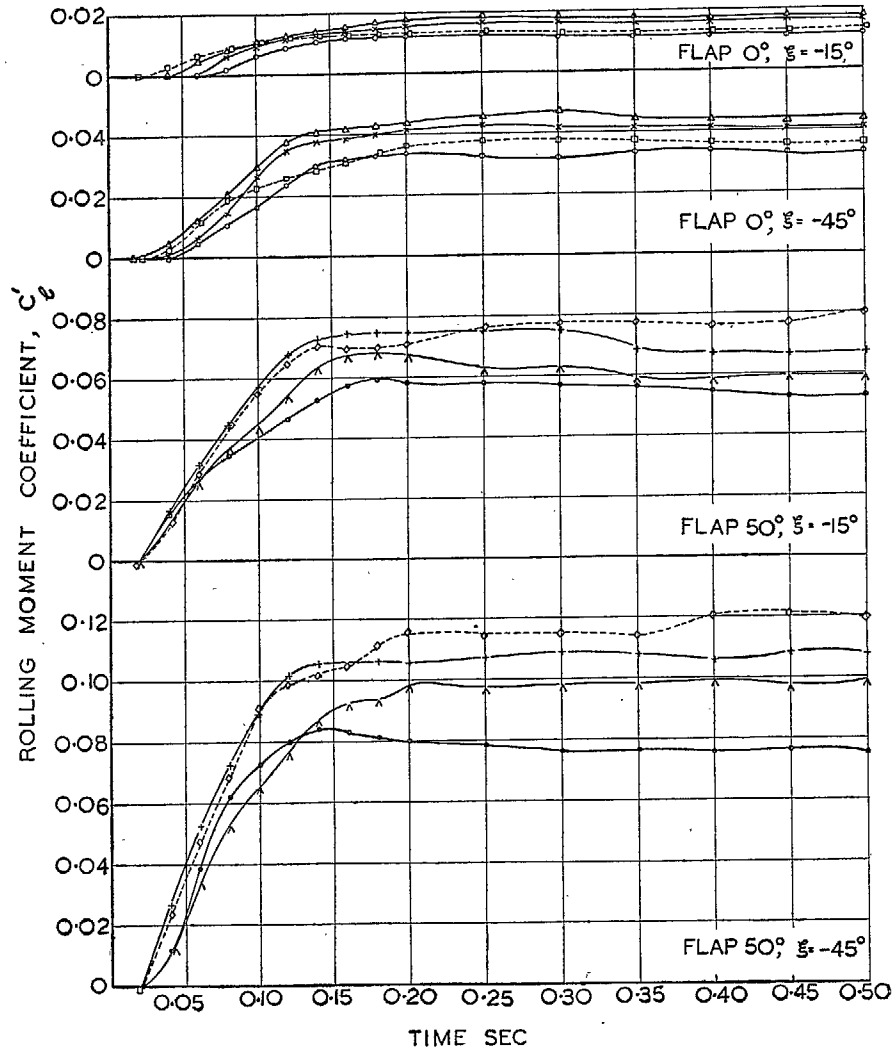


FIG. 12. Development of Rolling Moment with Time Due to Sudden Deflection of Spoiler (Fig. 2b). $\gamma = -31.5$ deg.

$\xi = -15$ deg., spoiler deflected in 0.016 sec.

$\xi = -45$ deg., spoiler deflected in 0.048 sec.

- $C_L \approx 0.02$, × $C_L \approx 0.40$, △ $C_L \approx 0.78$, □ $C_L \approx 1.09$.
- $C_L \approx 1.67$, ∧ $C_L \approx 2.00$, + $C_L \approx 2.38$, ◇ $C_L = 2.75$.

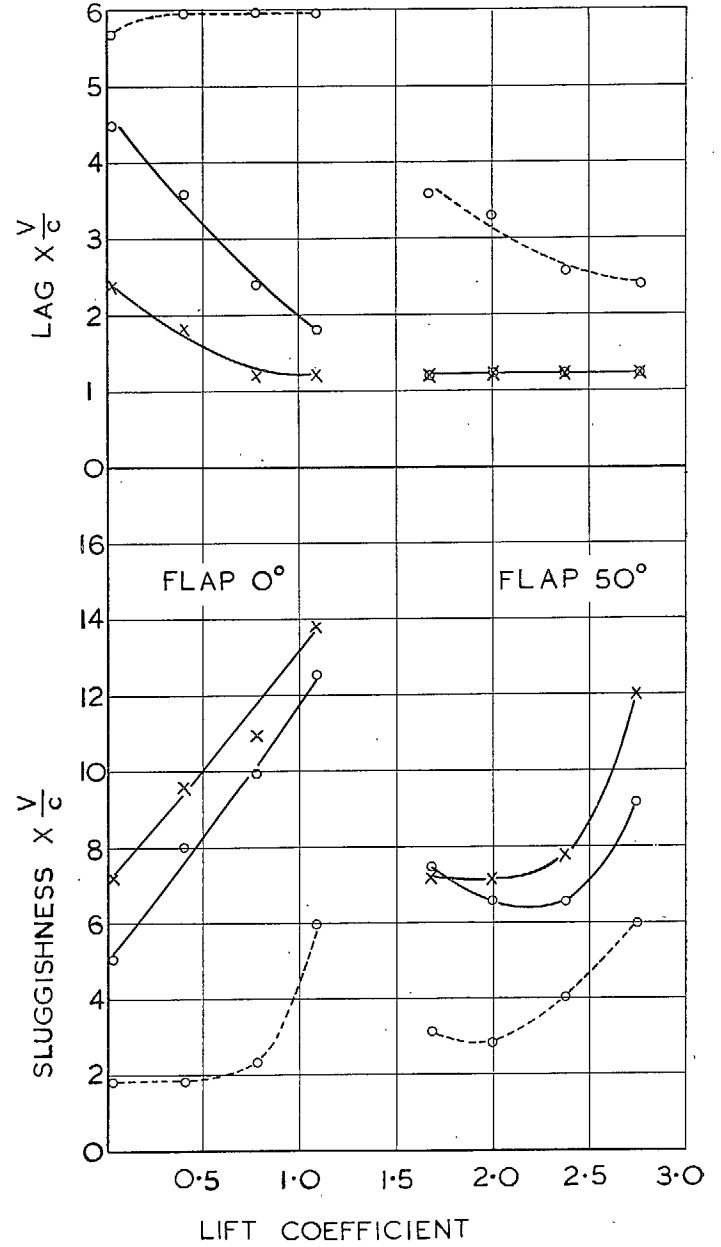


FIG. 13. Response Characteristics of Spoiler (Fig. 2b).

$\gamma = -31.5$ deg. ○ $\xi = -15$ deg, × $\xi = -45$ deg.
 — Slot open. - - - - Slot sealed.

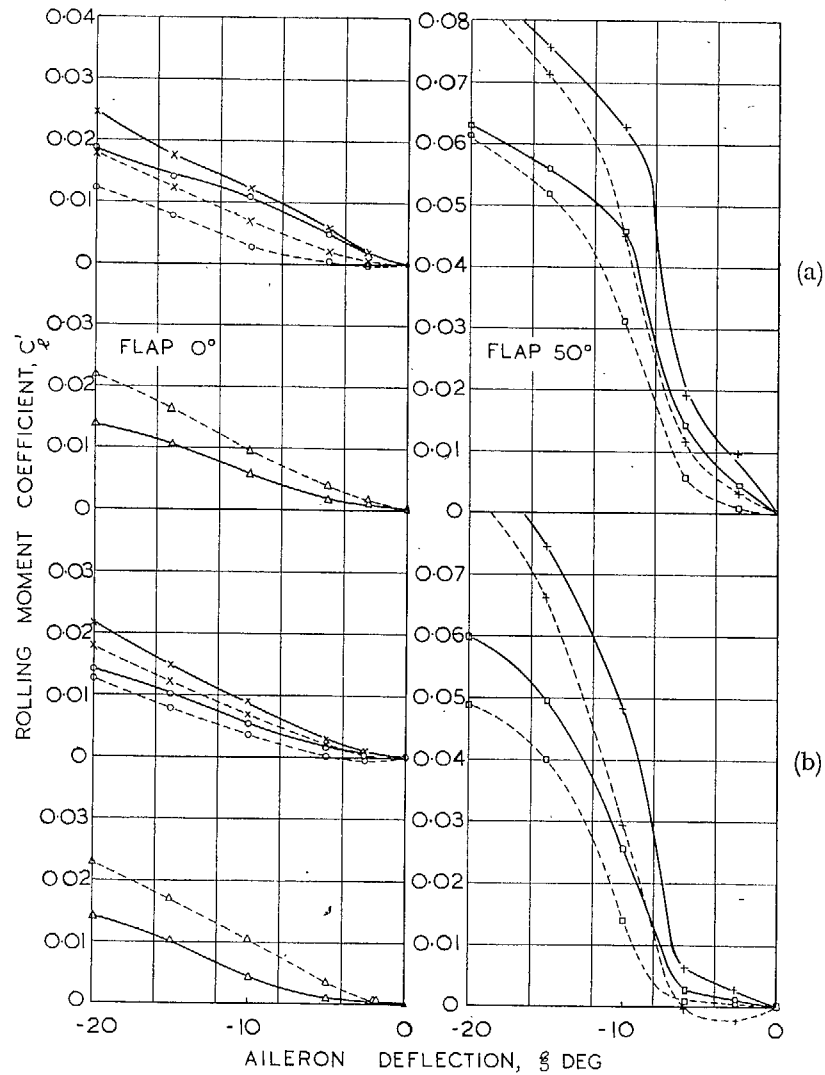


FIG. 14. Effect of Intersurface Slot on Rolling Moment for (a) the Spoiler (Fig. 2a), (b) the Spoiler (Fig. 2b) with $\gamma = -40$ deg.
 (Slot open ———. Slot sealed - - - - -).
 $\circ C_L \approx 0.03$, $\times C_L \approx 0.39$, $\triangle C_L \approx 1.04$, $\square C_L \approx 1.89$,
 $+ C_L \approx 2.76$.

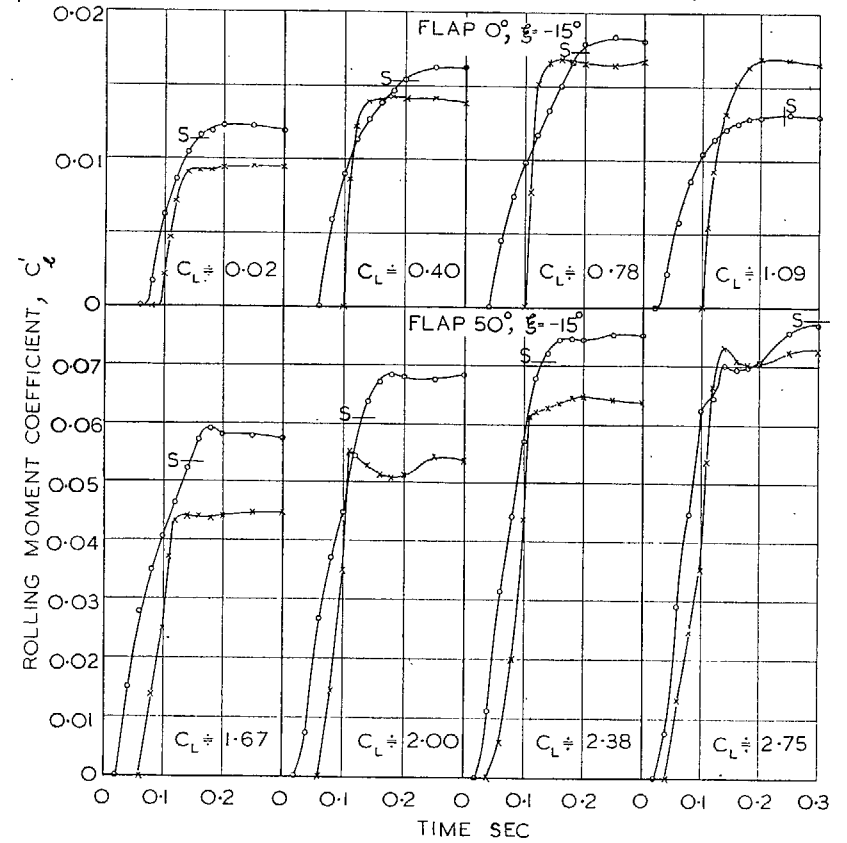


FIG. 15. Effect of Intersurface Slot on the Response of the Circular-arc Spoiler (Fig. 2b). $\gamma = -31.5$ deg. S indicates Static Rolling-moment Coefficient Slot Open (see Fig. 11). \circ Slot open. \times Slot sealed.

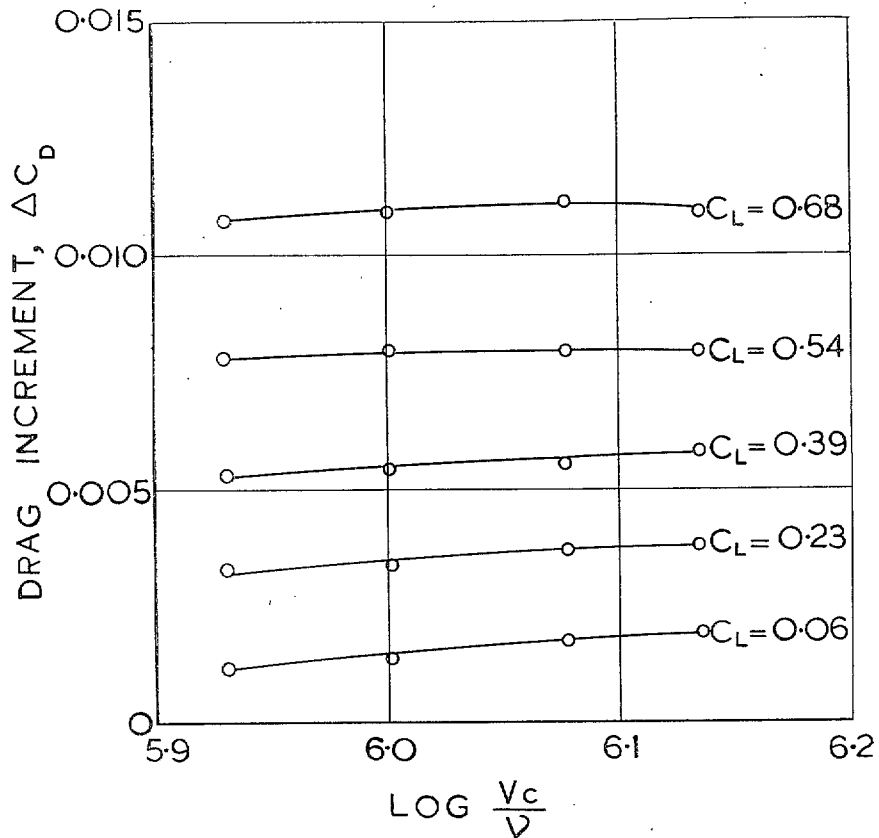


FIG. 16. Drag Increment due to the Intersurface Slot associated with the Circular-arc Spoilers of Figs. 2(a), 2(b), $\xi = 0$ deg.

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