C.P. No. 887

C.P. No. 887

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

A Developed Theory of Spoilers on Aerofoils

By

C. S Barnes, Ph.D.

LONDON: HER MAJESTY'S STATIONERY OFFICE

1966

Price 14s. 6d net

C.P. No.887

July, 1965

A Developed Theory of Spoilers on Aerofoils

by

C. S. Barnes, Ph.D.

Cambridge University Engineering Laboratory

Summary

A theory for the lift and pitching moment coefficients due to two-dimensional normal spoilers on aerofoils in incompressible flow was developed from that of Woods[11]. By making use of experiments on a symmetrical aerofoil fitted with spoilers, the displacement thickness of the boundary layer at the spoiler position and a measure of the pressure in the separated region behind the spoiler were taken into account.

These empirical modifications led to good agreement with experiment over a range of aerofoil incidence. Since a change of incidence is similar in many respects to a change of aerofoil shape it appeared likely that the modified theory would apply over a wide range of aerofoil sections.

Further experiments upon an aerofoil of considerably different shape provided confirmation, good agreement being obtained between theory and experiment.

A limited series of experiments was made on spoilers of finite span upon the original aerofoil. For spoilers of span greater than 80% of the aerofoil chord it was found that their lift and pitching moment increments could be correlated roughly with those due to two-dimensional spoilers.

Replaces A.R.C.27 123.

Contents

1. Introduction

Spoilers for lateral control of aircraft can take many forms. In order to illustrate the complexity of the problems involved in developing a theory for the behaviour of spoilers, it is convenient to consider briefly the various types of spoiler.

The simplest form of spoiler is a flat plate projecting normal to the aerofoil surface. A refinement of this type is the circular arc spoiler projecting through the aerofoil surface. A feature of the latter is its very small hinge moment if it is pivoted at its centre of curvature.

Hinged flap spoilers, which lie flush with the aerofoil surface when not in use, are normally hinged at or slightly upstream of their front edge and swing up through a controllable angle. When such spoilers are hinged upstream of their front edge, a gap opens beneath them when they swing up, allowing air to pass from upstream to downstream of them. Such venting, which reduces the response time[1,2] and also the tendency to buffet[3] may be accomplished in a variety of other ways.

The spoiler itself may be perforated[2], or air may be allowed to flow from the aerofoil lower surface into the region behind the spoiler. Spoiler-type devices which employ venting from the lower surface are the slot-lip aileron and the plug aileron[4].

The relative merits of spoilers and conventional flap-type ailerons have been summarised by Jones[5], who includes a substantial bibliography in his paper.

A very considerable amount of work has been carried out on spoilers, particularly in America. A paper by the Langley Research Staff[4] is a critical review of the lateral control research carried out by the NACA and a further collection of spoiler data is presented by Fischel and Ivey[6].

A series of two-dimensional spoiler tests at high subsonic speeds was undertaken at the National Physical Laboratory and reported by Pearcey and Pankhurst[7], and Pearcey, Pankhurst and Lee[8]. The manner in which the lift increment due to a spoiler arises is discussed in the former paper.

The majority of the work done has, however, been of the nature of development work or tests on particular installations. The variety of spoiler configurations tested is not in general sufficiently comprehensive to permit reliable quantitative estimates of spoiler effectiveness in a given design case.

Franks[9] put forward a method for predicting the rolling effectiveness of flat plate normal spoilers. It was developed for spoilers at 70% chord and employs a correlation between a limited number of spoiler and flap tests.

A more comprehensive theory was developed by Jones, Lamb and Cronk[10] for upper surface normal spoilers. They correlated the available spoiler data in terms of spoiler and wing planform parameters and chose a particular spoiler at a particular position on a particular wing planform to provide a basic value. Correction factors were then introduced to modify this basic value to that for other configurations. The parameter predicted is the rate of change of spoiler lift increment with spoiler height. This parameter was assumed to be independent of both angle of incidence and spoiler height. Both these assumptions are at variance with the results of the present investigation.

There remains a clear necessity for a theory which predicts the effectiveness of a given spoiler installation. The variety of possible wing and spoiler combinations suggests that the best approach is to take the simplest case initially and progress to more complex cases.

There are in existence two theories which attempt to predict the effects of two-dimensional unswept spoilers on aerofoils.

The first, due to Woods[11], has been shown to be in reasonable agreement with the results of Pearcey et al.[7,8] and those of Voepel[12], particularly for trailing edge spoilers. Although not a part of his theory, Woods recognises that the boundary layer approaching a spoiler plays an important part in determining the effects of a spoiler.

The second theory, due to Omori[13], is very much simpler than Woods' theory and from this point of view is initially more attractive. The results of this investigation showed Woods' theory to be in better agreement with experiment, however, and it was adopted for further use. Both theories are discussed in Section 3.2

The aims of this investigation were to carry out a systematic study of the effects of two-dimensional spoilers on aerofoils and to use the results obtained as a basis for checking, and for modifying if necessary, the available theories.

An experimental study was also made of finite spoilers upon aerofoils and some correlation was obtained between the results for those spoilers and for two-dimensional spoilers.

2. Notation

a_o lift curve slope of aerofoil alone

a_1 $\left(\frac{\partial C_L}{\partial \alpha}\right)_\delta$

a_2 $\left(\frac{\partial C_L}{\partial \delta}\right)_\alpha$

b base height defined by Eqn. (7.8)

c	aerofoil chord
C_{DS}	$\frac{D}{\frac{1}{2}\rho U^2 c}$
C_L	lift coefficient of aerofoil plus spoiler
C_{LS}	$\frac{L}{\frac{1}{2}\rho U^2 c}$
C_{LSS}	defined by Eqns. (11.1)
C_M	pitching moment coefficient of aerofoil plus spoiler
C_{MA}	pitching moment coefficient of the aerofoil alone
C_{MO}	pitching moment coefficient of the aerofoil alone at zero lift
C_{MS}	$\frac{M}{\frac{1}{2}\rho U^2 c^2}$
C_{MSS}	defined by Eqns. (11.1)
C_p	$\frac{p - p_1}{\frac{1}{2}\rho U^2}$ See Eqn. (3.1)
C_{po}	pressure coefficient on the aerofoil at zero lift with no spoiler
C_{ps}	increment of pressure coefficient due to incidence and to the spoiler, assuming that the pressure in the wake downstream of the aerofoil trailing edge is equal to p_1
C_{pw}	increment of pressure coefficient due to the actual pressure distribution in the wake downstream of the aerofoil trailing edge
$C_{p\sigma}$	assumed constant value of C_{ps} behind the spoiler
ΔC_p	incremental load coefficient, defined by Eqn. (3.13)
D	drag increment per unit span due to a two-dimensional spoiler on an aerofoil
E	$\frac{x_s}{c}$
F	function of β, plotted in Fig. 1
h	spoiler height
$\bar{h}$	effective spoiler height
H	boundary layer shape parameter
H_1	tunnel working section height

k	given by $\cosh \frac{k}{2} = 1 - 2 \sin \frac{\lambda}{2}$
ℓ	$\frac{1}{4}(1 + \sqrt{E})^2(\frac{k}{2} + \sinh \frac{k}{2})$
L	lift increment per unit span due to a two-dimensional spoiler
L_s	lift increment due to a finite span spoiler
m	$\frac{1}{16}(1 + \sqrt{E})^4(1 + \sin \frac{\lambda}{2})(2 \sin^2 \frac{\lambda}{2} + 2 \sin \frac{\lambda}{2} + 1)$
m_2	$\left(\frac{\partial C_M}{\partial \delta}\right)_\alpha$
M	pitching moment increment per unit span due to a two-dimensional spoiler
M_s	pitching moment increment due to a finite span spoiler
n	$\frac{1}{16}(1 + \sqrt{E})^4 \left\{\frac{1}{8}(1 + 4 \sin^2 \frac{\lambda}{2})(k + 2 \sinh \frac{k}{2}) + 4\sin \frac{\lambda}{2}(1 - \sin \frac{\lambda}{2})^2 + \frac{1}{2} \sinh \frac{k}{2}(1 - \sin \frac{\lambda}{2})\right\} - (1 + \sqrt{E})^2 \sin \frac{\lambda}{2}$
p	static pressure on aerofoil
p_1	free stream static pressure
R	$\frac{\rho U c}{\mu}$
s	spoiler span
U	free stream velocity
U_e	velocity at the outer edge of the boundary layer on the clean aerofoil
U_1	velocity over the spoiler tip
x	chordwise distance measured from the aerofoil leading edge
x_p	chordwise distance from the aerofoil leading edge to the incremental centre of pressure due to a spoiler
x_s	chordwise distance of a spoiler from the aerofoil leading edge
y	aerofoil ordinate measured normal to the chord
y_s	aerofoil ordinate at the spoiler position

α	aerofoil incidence
α_0	incidence of the aerofoil alone for zero lift
β	spoiler deflection angle in radians
γ	defined by Eqns. (3.4) and (3.9)
δ	lateral control deflection
δ^*	boundary layer displacement thickness at the spoiler position in the absence of the spoiler
λ	given by $\sin\frac{\lambda}{2} = \frac{\sqrt{E} - 1}{\sqrt{E} + 1}$
λ_1	defined by Eqns. (3.5) and (3.10)
μ	viscosity of air
ρ	density of air
ϕ	defined by Eqn. (7.9)

Note on Pitching Moment

All pitching moments are measured about the aerofoil leading edge.

3. Two-Dimensional Spoiler Theory

Before describing the available theories of two-dimensional spoilers upon aerofoils it is worthwhile considering the parameters involved.

3.1 Dimensional analysis

The independent variables governing the behaviour of an unswept two-dimensional spoiler of height h, assumed to be an infinitely thin flat plate at a distance x_s from the leading edge of an aerofoil of chord c, at incidence α, in incompressible flow of velocity U are:

$$h \quad \beta \quad c \quad x_s \quad \alpha \quad U \quad \rho \quad \mu \quad \text{Aerofoil Shape.}$$

The spoiler deflection angle is β, and ρ and μ are air density and viscosity respectively. Aerofoil shape must include surface roughness.

The dimensionless groups may be written as

$$\frac{h}{c} \quad E \quad \beta \quad \alpha \quad R \quad \text{Aerofoil Shape}$$

where $E = \frac{x_s}{c}$ and $R = \frac{\rho U c}{\mu}$.

Some simplification is made possible by considering the theory of Woods[11] which is further discussed in Sections 3.2.1 and 3.2.2. This is essentially an inviscid theory with mixed boundary conditions, so that there is no Reynolds number to be considered. The aerofoil thickness and angle of incidence are both assumed to be small so that variations of aerofoil shape and incidence have only second-order effects on the chordwise pressure distribution due to a spoiler and may be neglected**.

In a real fluid the effect of a spoiler may be expected to depend to some extent on the boundary layer thickness and velocity profile at the position of the spoiler. The boundary layer parameters are functions of the Reynolds number and the aerofoil shape and incidence.

It seems reasonable to assume, therefore, that in a real fluid the only significant effects, upon spoiler characteristics, of the Reynolds number, aerofoil shape and incidence are caused by the dependence of the boundary layer upon these variables.

Assuming that the boundary layer can be specified with sufficient accuracy by its displacement thickness δ^* and the single shape parameter H, the dimensionless groups governing the pressure distribution due to a spoiler may then be written as

$$\frac{h}{c} \qquad E \qquad \beta \qquad \frac{\delta^*}{h} \qquad H .$$

For a spoiler mounted far forward on the upper surface***, the velocity just outside the boundary layer at the position of the spoiler varies considerably with incidence and aerofoil shape and the assumptions may be inaccurate. However, such far forward spoiler positions are unlikely to be used in practice on account of the magnitude of the associated response time.[1,2]

3.2 Two-dimensional spoiler theories

The two theories available are very different and it is convenient to discuss them separately.

3.2.1 The theory of aerofoil spoilers by L.C. Woods[11]

Woods' theory is a mathematical treatment of two-dimensional aerofoil spoilers in subsonic flow. His calculations are based on

---

** Although the chordwise pressure distribution may be sensibly independent of aerofoil shape, integrations such as that to determine drag coefficient are clearly dependent upon that shape.

*** Henceforth the terms "upper surface" and "lower surface" will refer to the suction surface and pressure surface of an aerofoil respectively.

his extension of the Helmholtz theory of infinite constant-pressure wakes in incompressible flow, to infinite varying pressure wakes in subsonic compressible flow[14].

Woods demonstrates that if terms of the order of the square of the aerofoil thickness/chord ratio can be neglected then the pressure coefficient, C_p, on a symmetrical aerofoil fitted with a two-dimensional spoiler can be written as

$$C_p = C_{po} + C_{ps} + C_{pw} \qquad (3.1)$$

where C_{po} is due to the aerofoil shape at zero lift (with no spoiler), C_{ps} is the increment due to the spoiler plus aerofoil incidence, assuming free stream pressure in the wake downstream of the trailing edge, and C_{pw} is that due to the actual pressure distribution in that portion of the wake.

C_{pw} is a symmetrical term which is the same on both surfaces of the aerofoil at a given chordwise position. It therefore has no effect on the lift and pitching moment coefficients.

Eqn. (3.1) embodies Woods' assumption that the incremental pressure distribution due to a spoiler is independent of aerofoil shape for thin aerofoils at small incidences.

Although for simplicity the equations of Woods' theory will be written here for a symmetrical aerofoil, this is not a restriction. For aerofoils with positive camber the aerofoil incidence α in any equations for lift coefficient should be replaced by $(\alpha - \alpha_o)$, where α_o is the incidence for zero lift. A similar modification should be made to equations for pitching moment but an additional term C_{MO}, the pitching moment at zero lift, must be added.

The major difficulty in the application of Woods' theory is the well known problem of the magnitude of the base pressure in a separated region.[15] Between the spoiler and the aerofoil trailing edge Woods assumes the increment C_{ps} to be constant. It is not possible to check this assumption experimentally since the increments C_{ps} and C_{pw} cannot be separated.

A related problem occurs since the function λ_1, Eqn. (3.5) below, includes the velocity U_1 over the spoiler tip which can be most conveniently expressed in terms of the base pressure coefficient.

A third difficulty arises on account of the presence of the boundary layer upstream of a spoiler. The associated flow separation modifies the shape of the pressure distribution upstream and, in particular, reduces the magnitude of the pressure rise. This may be thought of as an effective reduction in spoiler height and Woods suggests replacing the actual spoiler height h by an effective spoiler height $\bar{h}$, somewhat less than h, where $h - \bar{h}$ might be a function of δ^*. Some justification for this is presented in Section 3.1.

3.2.2 The basic equations of Woods' theory for incompressible flow

The pressure distribution is given by

$$C_p - C_{po} = C_{pw} + \left\{2\alpha + \frac{\beta\lambda_1}{\pi} + \frac{kC_{p\sigma}}{2\pi}\right\} \frac{\text{Cos}\,\frac{\gamma}{2}}{\text{Sin}\,\frac{\lambda}{2} - \text{Sin}\,\frac{\gamma}{2}}$$

$$+ \frac{\beta\lambda_1}{\pi} \frac{\text{Cos}\,\frac{\gamma}{2}}{1 + \text{Sin}\,\frac{\gamma}{2}} + \frac{2C_{p\sigma}}{\pi} \text{Tan}^{-1}\left\{\text{Tan}\,\frac{1}{4}(\pi - \gamma)\text{Tanh}\,\frac{k}{4}\right\} \tag{3.2}$$

except between the spoiler and the trailing edge where

$$C_p - C_{po} = C_{pw} + C_{p\sigma} \tag{3.3}$$

where $C_{p\sigma}$ is independent of x. Aerofoil incidence must be measured in radians.

Position on the aerofoil chord is defined by γ which is given by

$$\sin\frac{\gamma}{2} = \pm \frac{2\sqrt{\frac{x}{c}}}{1 + \sqrt{E}} + \text{Sin}\,\frac{\lambda}{2} \tag{3.4}$$

and for a spoiler on the upper surface, γ runs from $-\pi$ at the spoiler to $+\pi$ at the lower surface trailing edge. It has no relevance in the region behind a spoiler.

The spoiler height appears in

$$\lambda_1 = F\sqrt{\frac{2\,\frac{h}{c}}{E + \sqrt{E}} \cdot \frac{U_1}{U}} \tag{3.5}$$

where F is a function of spoiler angle and is plotted in Fig. 1 from values given by Woods for incompressible flow.

The undefined symbols are included in the notation.

Integrations of Eqns. (3.2) and (3.3) yield the lift and pitching moment coefficients:

$$C_L = \frac{\pi}{2}(1 + \sqrt{E})^2\alpha - \beta\lambda_1(\sqrt{E} + E) - \frac{1}{4}(1 + \sqrt{E})^2(\frac{k}{2} + \text{Sinh}\frac{k}{2})C_{p\sigma}$$

$$= \frac{\pi}{2}(1 + \sqrt{E})^2\alpha - \beta\lambda_1(\sqrt{E} + E) - \ell\, C_{p\sigma} \qquad (3.6)$$

$$C_M = -\frac{\pi}{32}(1 + \sqrt{E})^4(1 + 4\,\text{Sin}^2\frac{\lambda}{2})\alpha$$

$$+ \beta\lambda_1 . \frac{1}{16}(1 + \sqrt{E})^4(1 + \text{Sin}\,\frac{\lambda}{2})(2\,\text{Sin}^2\frac{\lambda}{2} + 2\,\text{Sin}\,\frac{\lambda}{2} + 1)$$

$$+ C_{p\sigma}\frac{1}{16}(1 + \sqrt{E})^4\left\{\frac{1}{8}(1 + 4\,\text{Sin}^2\frac{\lambda}{2})(k + 2\,\text{Sinh}\frac{k}{2})\right.$$

$$\left. + 4\,\text{Sin}\,\frac{\lambda}{2}(1 - \text{Sin}\,\frac{\lambda}{2})^2 + \frac{1}{2}\,\text{Sinh}\frac{k}{2}(1 - \text{Sin}\,\frac{\lambda}{2})\right\}$$

$$- C_{p\sigma}(1 + \sqrt{E})^2\,\text{Sin}\,\frac{\lambda}{2}$$

$$= -\frac{\pi}{32}(1 + \sqrt{E})^4(1 + 4\,\text{Sin}^2\frac{\lambda}{2})\alpha + m\beta\lambda_1 + nC_{p\sigma} \qquad (3.7)$$

C_M is measured about the leading edge.

The variables ℓ, in Eqn. (3.6), and m and n in Eqn. (3.7) are functions of E only. They are plotted in Fig. 2.

Woods' expression in Ref. 11 for the incremental drag coefficient is not correct. It includes only the force on the upstream face of the spoiler. The force on the aerofoil surface is neglected and free stream pressure is assumed on the downstream face of the spoiler.

For the special case of a trailing-edge spoiler the above relations are much simplified since $C_{p\sigma}$ is no longer relevant and $E = 1$. Hence

$$C_p - C_{po} = C_{pw} - 2\alpha\text{Cot}\,\frac{\gamma}{2} + \frac{\beta\lambda_1}{\pi}\,\frac{\text{Sin}\,\frac{\gamma}{2} - 1}{\text{Sin}\,\frac{\gamma}{2}\,\text{Cos}\,\frac{\gamma}{2}} \qquad (3.8)$$

and

$$\text{Sin}\,\frac{\gamma}{2} = \pm\sqrt{\frac{x}{c}}\ , \qquad (3.9)$$

where the positive sign refers to the lower surface.

$$\lambda_1 = F\sqrt{\frac{h}{c} \cdot \frac{U_1}{U}} \tag{3.10}$$

$$C_L = 2\pi\alpha - 2\beta\lambda_1 \tag{3.11}$$

$$C_M = -\frac{\pi}{2}\alpha + \beta\lambda_1 \ . \tag{3.12}$$

In addition the incremental load coefficient due to the spoiler alone, i.e. neglecting incidence terms, reduces to

$$\Delta C_p = \left\{ C_{ps(\text{lower surface})} - C_{ps(\text{upper surface})} \right\}_{\alpha=0} \tag{3.13}$$

$$= -\frac{4\beta\lambda_1}{\pi} \operatorname{Cosec} \gamma \tag{3.14}$$

where $\pi \geqslant \gamma \geqslant 0$.

The above equations refer to spoilers on the upper surface. For a spoiler on the lower surface the terms in aerofoil incidence are unchanged and the remaining terms are changed in sign only. For spoilers ahead of the trailing edge this change only in sign seems inadequate. For this case Woods states that the spoiler has the "effect of cancelling out the effectiveness of part of the aerofoil". Physically, it seems reasonable that the effectiveness of different parts of the aerofoil, and hence different parts of the lift, would be cancelled for spoilers on the upper or on the lower surface.

3.2.3 The theory of spoilers by Y. Omori[13]

The merit of Omori's theory is its relative simplicity compared with that of Woods.

Omori uses a distribution of sources and sinks to approximate to the flow round a two-dimensional circular cylinder fitted with a spoiler normal to its surface. The flow in the cylinder plane is conformally transformed into the flow round a flat plate, at zero incidence, fitted with a normal spoiler.

This theory then neglects from the start any effect of aerofoil shape or incidence.

Comparison of the predictions of Omori's theory with the results of this investigation revealed serious discrepancies. At the same time it did not seem possible to allow for any variation with aerofoil incidence.

The theory of Woods was found to be much more satisfactory and has, therefore, been used as a basis for this work.

4. Experiments with Two-Dimensional Spoilers

For reasons of availability, two nominally identical open return wind tunnels were used each having a rectangular working section of width 28 in. and height 20 in.

Two model aerofoils were used while developing the spoiler theory. Both were of RAE102 12% thick symmetrical section. One, of 15 in. chord, was constructed of laminated mahogany and used for obtaining pressure distributions. The other, of 7.9 in. chord, was machined from a solid dural block and was used for obtaining force measurements.

Provision was made for conducting boundary layer traverses on the upper surfaces of the aerofoils.

4.1 Pressure distributions

The 15 in. chord aerofoil was provided with a chordwise line of 29 pressure holes on the upper surface and 17 on the lower surface, both lines being at the centre of the span. The positions of the pressure tappings are given in Table 1.

The aerofoil, completely spanning the tunnel, was mounted horizontally in order to facilitate flow visualisation tests using the surface oil film technique. It was mounted upon a turntable fitted with a sensitive inclinometer such that its incidence could be set with an accuracy of $\pm$ 1 min. of arc.

Boundary layer transition was fixed by a trip wire at 12% chord on each surface.

Four spanwise rows of spoiler attachment holes enabled spoilers to be tested on the upper surface at the chordwise positions specified in Table 2. The position specified in each case is the position of the front face of the spoiler.

All the tests were carried out at a tunnel speed of approximately 93 ft/sec, giving $R = 7.4 \times 10^5$.

The boundary layer development on the upper surface of the clean aerofoil was determined at incidences of 0°, 4° and 8° (Table 5). The velocity profiles indicated that the boundary layer was turbulent and this was confirmed by the use of a stethoscope attached to a pitot tube.

Pressure distributions for the clean aerofoil were obtained at the above incidences. The pressure distributions for each of the three spoiler heights noted in Table 3 at the four chordwise positions of Table 2 were similarly obtained.

The surface oil film technique was used to determine whether the flow reattached behind any of the spoilers.

4.2 Force measurements

The 7.9 chord aerofoil was geometrically similar to the 15 in. chord aerofoil, in all respects, including trip wire position and relative diameter, and the spoiler attachment positions.

The former model was fitted with attachment points for suspension from a three component aerodynamic balance and completely spanned the tunnel apart from a clearance of approximately 0.02 in. between each tip and the tunnel wall. The suspension wires used were of 22 s.w.g. piano wire.

The model was mounted in the conventional manner for a roof balance such that the lift of the clean aerofoil acted downwards. The lift increment due to a spoiler on the upper surface (using the convention of P.6) thus acted upwards and tended to slacken the suspension wires. Extra weights were hung from the model on wires extending through the tunnel floor to prevent such slackening.

A template fitted with a sensitive inclinometer enabled the model incidence to be set with an accuracy of $\pm$ 1 min. of arc.

The tests were carried out at a tunnel speed of approximately 101 ft/sec giving $R = 4.3 \times 10^5$.

Since the two RAE102 models were geometrically similar, it was hoped that in spite of the difference in Reynolds number, their boundary layer developments would also be similar, facilitating comparisons between the results for nominally identical spoiler installations on the two aerofoils.

At $\alpha = 0°$, 4° and 8° the boundary layer velocity profiles near the trailing edge, obtained using a pitot comb, corresponded closely to those at a similar position on the pressure plotting aerofoil when expressed non-dimensionally. The boundary layer developments on the upper surface of both aerofoils were therefore assumed to be similar at a given incidence.

Lift, drag and pitching moment measurements at $\alpha = 0°$, 4° and 8° were made for the clean aerofoil and for the aerofoil fitted with spoilers, with the spoiler positions and heights noted in Tables 2 and 3.

4.3 The spoilers

The non-dimensional heights of the spoilers tested are noted in Table 3. These are identical for the two RAE102 aerofoils.

The spoilers tested at the three positions ahead of the trailing edge were made from $\frac{1}{16}$ in. thick, 90° brass angle. The downstream face of each spoiler was machined at its tip to form a 30° knife edge. Details of the spoilers used, all of which were mounted normal to the surface, are sketched in Fig. 3. Dummy lugs identical to that part of the trailing edge spoiler attachment screwed to the lower surface were also made. Tests with the dummy lugs showed no detectable effects upon the forces measured for the clean aerofoil.

In all cases any gaps between the spoilers and the aerofoil were sealed to prevent leaks.

5. Wind Tunnel Interference

The magnitude of wind tunnel interference is more uncertain in the presence of separated flow than with fully attached flow. The theory of Maskell[16] provides a value for the blockage effect in the presence of separated flow, but the "lift effect", the effect of induced streamline curvature, cannot be readily evaluated. The latter will presumably influence the downstream path of the wake.

The lift effect theory of Glauert[17], for two-dimensional aerofoils of small chord at small incidences, replaces the model and its images in the tunnel walls by vortices. The vortex replacing the model is situated at the model's centre of pressure. A limited extension was made to this theory in terms of the position on the chord of the centre of pressure of an aerofoil fitted with a two-dimensional spoiler and summing the infinite power series in $\left(\frac{c}{H_1}\right)^2$ obtained, where H_1 is the tunnel height.

In the hope that applying the above two corrections would prove satisfactory, the relatively large chord RAE102 12% thick, symmetrical aerofoil was employed to obtain pressure distributions (Section 4.1) so that the maximum possible Reynolds number was obtained. The second RAE102 aerofoil, of approximately half the chord, was used to obtain direct measurements of the aerodynamic forces (Section 4.2) and provided a comparison between the two sets of corrected results.

This comparison revealed a substantial discrepancy, the form of which suggested that the tunnel interference corrections applied were too large. It could possibly have been due, however, to a lack of two-dimensional flow near the tips of the balance model, leading to spanwise pressure gradients.

In order to examine the possibility of three-dimensional flow, a series of investigations using the RAE102 balance model, but with varying values of $\frac{c}{H_1}$, was undertaken by modifying the tunnel working section.

Two such modifications were made, involving reductions in height to 13.9 in. and 10.5 in. They were effected by inserting two sheets of 0.5 in. plywood into the working section at the required distance apart. Upstream, two sheets of 28 s.w.g. sheet steel, cut to the required shape, were used to fair into the tunnel contraction. Downstream, two further sheets of 0.5 in. plywood joined the ends of the new roof and floor to the diffuser roof and floor. In the 10.5 in. case the diffuser angle became considerable, and in order to inhibit flow separation, simple triangular, counterrotating, monoplane* vortex generators were introduced at the start of the new diffuser. These were 1 in. in height, set at 20° to the flow and 2.5 in. apart and delayed separation until far downstream close to the fan.

The false roof and floor were adjusted in each case to give a zero pressure gradient in the empty working section at the tunnel speed required. They were attached rigidly by a number of ties to the tunnel framework in order to prevent any flexing due to a pressure difference across them. All gaps were sealed.

Both modified working sections were calibrated in terms of an upstream reference pressure difference.

Initial measurements were made using the modified working section of height 10.5 in., giving $\frac{c}{H_1} = 0.75$, the same value as for the 15 in. chord pressure plotting aerofoil. A full series of balance tests with this configuration yielded uncorrected results which were in excellent agreement with the uncorrected results obtained from the pressure plotting aerofoil. It was concluded that the three-dimensionality was negligible and that the discrepancies arose due to inaccurate tunnel interference corrections.

A further full set of results for the balance model was obtained with the modified tunnel height equal to 13.9 in.

The corresponding values from the three sets of results obtained with this model were plotted against $\frac{c}{H_1}$ and extrapolated to infinite tunnel height, i.e. to $\frac{c}{H_1} = 0$, giving, it is thought, reliable interference-free values.

6. Experimental Results

Figs. 4, 5, 6 and 7 show typical measured pressure distributions about the 15 in. chord aerofoil when fitted with a two-dimensional spoiler of height $\frac{h}{c} = 0.047$. Figs. 4 and 5, for $\alpha = 0°$ and 8° respectively, with the spoiler at the trailing edge, also include the corresponding pressure distributions for the plain aerofoil. Figs. 6 and 7, for $\alpha = 0°$ and 8° respectively, each show the pressure distributions for a spoiler at $E = 0.49$ and 0.89.

The pressure distributions presented have not been corrected for tunnel interference and hence they differ in detail from free air values. The values given for the lift and pitching moment coefficients in Figs. 8 to 11 were obtained using the 7.9 in. chord

---

* This is the notation of Tanner, Pearcey and Tracy[18].

balance model and have been corrected for tunnel interference by the extrapolation method described in Section 5.

Figs. 8 and 9 are curves of the incremental lift coefficient due to spoilers at $E = 1.0$ and 0.49 respectively. They are plotted against $\frac{h}{c}$ for various incidences.

Figs. 10 and 11 illustrate the variation with E, at constant $\frac{h}{c}$ and α, of the experimental incremental lift and pitching moment coefficients due to a two-dimensional spoiler of $\frac{h}{c} = 0.047$. The variation with E is typical of the other spoiler heights also.

7. Development of Woods' Theory for the Lift due to a Spoiler

Since Woods' theory is very much simpler for spoilers at the trailing edge (Section 3.2.2), it is convenient to consider first the results for that case in terms of his theory and of the modifications to that theory required to introduce the effects of a real fluid.

Inspection of Figs. 4 and 5 reveals that at each incidence the spoiler, on the upper surface, induces a fairly constant increase in pressure over most of the upper surface and a similar decrease in pressure on the lower surface. The reduction in pressure on the lower surface seems to be controlled mainly by the magnitude of the pressure in the wake region behind the spoiler. Close to the leading edge, the change in the pressure distribution is rather like that due to a decrease in incidence, since the reduction of circulation involves a movement of the stagnation point towards the upper surface.

At a given value of $\frac{x}{c}$ on the upper surface, the value of the pressure increment due to the spoiler decreases as α increases. This effect is probably caused by the increase of boundary layer thickness with α; a similar effect for a fence on a flat plate is described in Ref. 19.

As is suggested in Section 3.2.1 the effect of the boundary layer approaching a spoiler may be equivalent to a reduction in spoiler height. The dimensional analysis of Section 3.1 indicates that any such effective reduction in spoiler height should be a function of $\frac{\delta^*}{h}$ and H.

The variation with α of the experimental values of the incremental lift coefficient C_{LS}, shown in Fig. 8, supports the hypothesis of an effective reduction in spoiler height.

7.1 Incremental load coefficient distribution

Before considering in detail the required modifications to Woods' theory, the unmodified theory must be shown to be a reasonable representation of the overall effects of a spoiler.

Fig. 12 shows plots at $\alpha = 0°$ and $4°$ of the incremental load coefficient ΔC_p, defined by Eqn. (3.13), due to the spoiler of $\frac{h}{c} = 0.047$. The theoretical distribution is proportional to Cosec γ (Eqn. (3.14)) and a curve of this type is included in Fig. 12. The theoretical curve was chosen as 0.6 Cosec γ in order to give approximate coincidence with experiment. It was not worthwhile to use the theoretical value of the constant, since the experimental curves were not corrected for tunnel interference.

There is seen to be a marked similarity between the shape of the experimental and theoretical distributions. Some of the discrepancy near the trailing edge is due to boundary layer separation upstream of the spoiler.

7.2 Incremental lift coefficient

Woods' expression, Eqn. (3.11), for the lift coefficient of an aerofoil fitted with a two-dimensional trailing edge spoiler, includes the term $2\pi\alpha$, which is the usual value given by thin aerofoil theory for the lift coefficient of a symmetrical aerofoil at incidence α.

Since the actual lift curve slope of an aerofoil will in general be known, it is more accurate to write Eqn. (3.11) as

$$C_L = a_o\alpha - 2\beta\lambda_1$$

where a_o is the actual lift curve slope. The incremental lift coefficient C_{LS} due to a spoiler is then given by

$$\left.\begin{aligned} C_{LS} &= C_L - a_o\alpha \\ &= - 2\beta\lambda_1 \ . \end{aligned}\right\} \qquad (7.1)$$

The value of C_{LS} which must be predicted is now that of Eqns. (7.1) where C_L and $a_o\alpha$ were both obtained experimentally. Inspection of Eqn. (3.10) for λ_1 reveals that the velocity U_1 over the spoiler tip must first be determined.

7.2.1 Velocity over the spoiler tip

In real fluid flow the velocity at the spoiler tip is of course zero. With increasing distance from the tip the flow velocity varies until it ultimately becomes constant and equal to the free stream velocity. In Woods' theory, which assumes a finite velocity at the spoiler tip, this velocity can be conveniently expressed in terms of the pressure coefficient on the downstream face of the spoiler, just below the tip. This pressure coefficient can be obtained experimentally. For convenience, the measured pressure coefficient at the downstream base of the spoiler was assumed to be equal to the required pressure coefficient.

Values of $\frac{U_1}{U}$ obtained in this way for each spoiler at each incidence were found to lie on a smooth curve when plotted against $\frac{\delta^*}{h}$.

7.2.2 Effective spoiler height

When the values of $\frac{U_1}{U}$ determined above were put into Woods' expression for C_{LS}, it was found that in all cases the numerical value of C_{LS} obtained exceeded the corresponding experimental value if the full value of $\frac{h}{c}$ was used.

An effective spoiler height $\bar{h}$ was then introduced, as suggested by Woods, so that λ_1 could be written

$$\lambda_1 = F\sqrt{\frac{h}{c} \cdot \frac{\bar{h}}{h} \cdot \frac{U_1}{U}} \tag{7.2}$$

where it was assumed that $\frac{\bar{h}}{h}$ would be a function of $\frac{\delta^*}{h}$ and H.

Using the value of $\frac{U_1}{U}$ determined above, the values of $\frac{\bar{h}}{h}$ required to predict the correct values of C_{LS} were obtained using Eqns. (7.1). The resulting values of $\frac{\bar{h}}{h}$ were found to lie on a smooth curve when plotted against $\frac{\delta^*}{h}$.

Since $\frac{\bar{h}}{h}$ and $\frac{U_1}{U}$ could both be expressed as functions of $\frac{\delta^*}{h}$ it was convenient to combine them as $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$, the form in which they occur in the expression for λ_1. This procedure also eliminated any error in $\frac{U_1}{U}$ due to the uncertain magnitude of wind tunnel interference upon the pressure measurements, since the required values of $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ were determined directly, using the experimental values of C_{LS}.

Fig. 13 illustrates the dependence of $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ upon $\frac{\delta^*}{h}$ only. The values of H for the trailing edge boundary layer profiles ranged from 1.7 to 2.7 between 0° and 8° but this large variation seemed to have no significant effect.

The empirical relation

$$\frac{\bar{h}}{h} \cdot \frac{U_1}{U} = 1.22 \left(0.1^{\frac{\delta^*}{h}}\right) \qquad (7.3)$$

was found to provide a satisfactory fit with a maximum error of ± 5% in the range considered. It was used with success for an aerofoil of considerably different shape (Section 9).

The lift increments predicted using the values given by Eqn. (7.3) for $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ in conjunction with Eqns. (7.2) and (7.1) are plotted in Fig. 14. The agreement with experiment is seen to be excellent over the whole range of spoiler height and aerofoil incidence. It appears that α is significant only for the manner in which it affects δ^*. This is confirmed by further experiments referred to in Section 9.

7.3 Two-dimensional spoilers ahead of the trailing edge

Inspection of Figs. 6 and 7 reveals that upstream of an upper surface spoiler ahead of the trailing edge, the upper surface pressure distribution at a given aerofoil incidence is rather like that for a trailing edge spoiler (Figs. 4 and 5). The lower surface pressure distributions are very like those of the trailing edge case. On the upper surface between the spoiler and the trailing edge the pressure is sensibly constant which suggests that there is no flow reattachment in this region. The oil film tests confirmed that there was no reattachment behind any of the spoilers tested.

Comparisons with the pressure distributions for the clean aerofoil, included in Figs. 4 and 5, show that the pressure increment at a given value of $\frac{x}{c}$, upstream of a spoiler at $E = 0.89$, decreases with increasing aerofoil incidence. This relationship is similar to that for trailing edge spoilers and can be related to increasing boundary layer thickness in the same way. A reverse trend is noticed for $E = 0.49$, however. The upstream pressure increment then increases with α, apparently on account of the large change, with α, in the pressure coefficient at the spoiler position on the clean aerofoil.

The pressure coefficient at the trailing edge of the clean aerofoil is only slightly dependent upon incidence. On the aerofoil upper surface the dependence of C_p on α of course increases very considerably towards the leading edge as the velocity at the outer edge of the boundary, U_e say, becomes increasingly greater than free stream velocity with increasing incidence. A spoiler reasonbly far forward on the aerofoil chord, such as that at $E = 0.49$, is thus in a region where U_e increases rapidly with incidence and the change induced in the aerofoil pressure distribution by the spoiler is dependent upon U_e.

When this occurs it is clear that the assumptions made by Woods, specifying thin aerofoils at small incidences, are breaking down. The significance of the parameter $\frac{\delta^*}{h}$ is reduced in that it alone is no longer sufficient to specify completely the effect of aerofoil shape and incidence since even in inviscid flow these parameters would have a considerable effect. The effect of a spoiler will still be reduced by the presence of the boundary layer but this reduction may be offset when U_e is appreciably greater than free stream velocity.

7.4 Modified Woods' theory for spoilers ahead of the trailing edge

When applying Woods' theory to spoilers ahead of the trailing edge, it is a simplification to retain the empirical relation for $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ evolved for trailing edge spoilers, (Eqn. (7.3)). A difficulty is that $\frac{U_1}{U}$ becomes increasingly dependent on U_e as E decreases but neglect of such a dependence is inherent in the assumptions of Woods' theory.

The parameter, $C_{p\sigma}$, in Woods' theory must be predicted empirically. Its definition, from Eqn. (3.3), as a constant on the aerofoil surface behind a spoiler, implies that $C_{p\sigma}$ will be a function of $\frac{h}{c}$, E and α for a given aerofoil.

Reference to the results obtained by Barnes[19] for normal fences on a flat plate, suggests that base pressure may be dependent mainly on the geometry of the solid boundaries rather than on the boundary layer parameters at the spoiler position. Similarly, Reynolds number should not be an important parameter. The flow in those experiments reattached on the plate downstream of the spoilers, whereas there was no reattachment in the present series of experiments with spoilers on aerofoils, but it seems reasonable to attempt to relate $C_{p\sigma}$ to the boundary geometry.

It is clear that for $C_{p\sigma}$ to have any physical significance as a form of base pressure coefficient, some such relationship must exist between it and the parameters describing the flow.

As noted in Section 7.5 it was found that $C_{p\sigma}$ could be expressed as a function of $\frac{h}{c}$ and a non-dimensional base height, $\frac{b}{c}$, defined by Eqn. (7.8). The base height is effectively a measure of the size of the separated region.

7.5 Incremental lift coefficient

The effect on the lift increment of the changing dependence upon α of the pressure increments upstream of a spoiler as E decreases, is clearly shown in Fig. 10.

The lift increments are defined by

$$C_{LS} = C_L - a_o\alpha$$

where $a_o\alpha$ is the lift coefficient of the clean aerofoil.

For the spoilers at the trailing edge, $\frac{\delta^*}{h}$ increases rapidly with α but U_e is nearly constant, and consequently the spoiler effectiveness decreases with increasing incidence. For the spoiler at $E = 0.49$, however, $\frac{\delta^*}{h}$ is less, and also increases less rapidly with α, but U_e increases rapidly. The spoiler effectiveness thus increases with α.

This implies that the lift curve slope, a_1, of an aerofoil fitted with a spoiler decreases as E decreases. This decrease in a_1 is related above to changes in the pressure distribution upstream of a spoiler on the upper surface, ignoring any changes with α of the incremental pressure distributions behind the spoiler or on the lower surface. Close inspection of the pressure distributions for the aerofoil with and without a spoiler shows that the major changes in pressure increments take place upstream of the spoiler.

Differentiation of Woods' expression for the lift coefficient, Eqn. (3.6) yields

$$a_1 = \frac{\pi}{2}(1 + \sqrt{E})^2 \qquad (7.4)$$

neglecting any dependence of $C_{p\sigma}$ upon α. Eqn. (7.4) gives decreasing a_1 with decreasing E but the reason for this given by Woods is wrong. Woods states that the spoiler cancels out the effectiveness of part of the aerofoil and Eqn. (7.4) is an expression of this statement.

This is not consistent with experiment since the results show that the change in a_1 is due to an increase in effectiveness of the spoiler rather than to any loss of effectiveness of the aerofoil itself.

On account of this discrepancy it was found much more convenient to re-write Eqn. (3.6) as

$$C_L = a_o\alpha - \beta\lambda_1(\sqrt{E} + E) - \ell\, C_{p\sigma} \qquad (7.5)$$

so that

$$C_{LS} = -\beta\lambda_1(\sqrt{E} + E) - \ell\, C_{p\sigma} \,. \qquad (7.6)$$

The increased effectiveness of a spoiler far forward on the chord could then be allowed for by choosing $C_{p\sigma}$ correctly. Clearly an individual value of $C_{p\sigma}$ could be chosen to enable correct prediction of the lift increment due to a given spoiler at given values of E and α but this value of $C_{p\sigma}$ must also be that required to predict the associated pitching moment correctly. A number of such values of $C_{p\sigma}$ must in addition depend systematically upon $\frac{h}{c}$, E and α. If either of the above conditions cannot be satisfied then Eqn. (7.5) is invalid.

The expression for λ_1, Eqn. (3.5) was re-written as

$$\lambda_1 = F\sqrt{\frac{2}{E+\sqrt{E}} \cdot \frac{h}{c} \cdot \frac{\bar{h}}{h} \cdot \frac{U_1}{U}} \qquad (7.7)$$

and Eqn. (7.3) was used to determine the values of $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ as functions of $\frac{\delta^*}{h}$, as for the trailing edge spoilers.

Using the value of ℓ given in Fig. 2, and those of λ_1 as determined above, the experimental values of C_{LS} were found from Eqn. (7.6).

Some means of expressing $C_{p\sigma}$ as a function of $\frac{h}{c}$, E and α was then required. In order to introduce the geometry of the solid boundaries an effective base height b was defined as shown in Fig. 15. It is seen that b is the distance of the spoiler tip from the aerofoil trailing edge, measured normal to the free stream direction.

Expressed non-dimensionally the base height is given as

$$\frac{b}{c} = (1 - E)\mathrm{Sin}\alpha + \frac{y_s}{c}\mathrm{Cos}\alpha + \frac{h}{c}\mathrm{Cos}(\alpha + \phi) \qquad (7.8)$$

for normal spoilers on the upper surface, where

$$\mathrm{Tan}\phi = -\frac{dy}{dx}_{x=x_s} \qquad (7.9)$$

Plots of $C_{p\sigma}$ against $\frac{b}{c}$ in Fig. 16, are seen to be linear relationships dependent on $\frac{h}{c}$. An adequate expression for $C_{p\sigma}$ was

$$C_{p\sigma} = 2\,\frac{b}{c} - 2.5\,\frac{h}{c} - 0.18\ . \qquad (7.10)$$

The form of the parameter $\frac{b}{c}$ effectively introduces a dependence of $C_{p\sigma}$ upon U_e. The major variation with incidence in Eqn. (7.8) is supplied by the term $(1 - E)\text{Sin}\alpha$ which is relatively unimportant for spoilers close to the trailing edge where E is close to unity, and increases in importance as E decreases. The variation of this term with E and α is thus rather like the dependence of the pressure increments on U_e on the upper surface and might be expected to describe this dependence reasonably well for conventional subsonic aerofoil sections.

Evidence of the successful application of Eqn. (7.10) to a different aerofoil section is given in Section 9.

An expression similar to Eqn. (7.8) could be obtained for spoilers on the lower surface but its dependence upon E and α could not be expected to be so favourable. However, spoilers are unlikely to be used on the lower surface since the direction of their associated yawing moment would then be unfavourable.

Figs. 17, 18 and 19 show the values of C_{LS} predicted using Eqn. (7.6), with the values of $C_{p\sigma}$ given by Eqn. (7.10), together with the corresponding experimental values. The value of ℓ for each value of E was found from Fig. 2. The agreement obtained between theory and experiment is seen to be very satisfactory for the range of spoiler height and position and aerofoil incidence.

Since the effect of varying α has been expressed completely by changes in $\frac{\delta^*}{h}$ and $\frac{b}{c}$ it seems reasonable that the modified theory should apply also to spoilers on other aerofoil sections. A change of section shape resembles, in many respects, a change of aerofoil incidence.

It is shown in Section 9, that the use of Eqn. (7.6) for C_{LS} in conjunction with Eqns. (7.7) and (7.10) proved equally satisfactory for two-dimensional spoilers on an aerofoil of considerably different section.

8. Incremental Pitching Moment Coefficient

It is again convenient when developing Woods' theory to consider first the case of spoilers at the trailing edge.

Woods' expression, Eqn. (3.12), for the pitching moment coefficient of an aerofoil fitted with a trailing edge spoiler, is similar to that for the lift coefficient, in that it includes a term common to thin aerofoil theory for symmetrical aerofoils. The term in this case, $-\frac{\pi}{2}\alpha$, implies that the centre of pressure of the clean aerofoil is at the quarter-chord point and that the lift curve slope is 2π. Pitching moment is measured about the leading edge.

Since the pitching moment dependence upon α for the clean aerofoil is known, it is more accurate to write the incremental pitching moment coefficient as

$$\left.\begin{aligned} C_{MS} &= C_M - C_{MA} \\ &= \beta\lambda_1 \end{aligned}\right\} \qquad (8.1)$$

where C_{MA} is the measured pitching moment coefficient of the clean aerofoil.

Comparison of Eqns. (8.1) with Eqns. (7.1) reveals that

$$\frac{C_{MS}}{C_{LS}} = -\frac{1}{2} \qquad (8.2)$$

implying that the incremental centre of pressure is at the mid-chord point. This arises because the theoretical incremental load coefficient for a trailing edge spoiler is proportional to Cosec γ which is symmetrical about $\frac{x}{c} = 0.5$.

Examination of the relationship between the experimental values of C_{MS} and C_{LS} revealed that the ratio $-\frac{C_{MS}}{C_{LS}}$ was closely equal to 0.47, 6% less than the theoretical value. The difference between experiment and theory was due to modification of the shape of the pressure distribution just upstream of the spoiler by the flow separation in that region.

The theoretical curves in Fig. 20 were obtained using the relation

$$\frac{C_{MS}}{C_{LS}} = -0.47 \qquad (8.3)$$

where the value of C_{LS} was that determined using the modified theory of Section 7.2. Eqn. (8.3) is therefore suggested for use with two-dimensional trailing edge spoilers. The value of 0.47 is in good agreement with the results of Voepel[12].

8.1 Spoilers ahead of the trailing edge

Having re-written Woods' expression, Eqn. (3.6), for C_L, his expression, Eqn. (3.7), for C_M must be treated similarly. Eqn. (3.7) then becomes

$$C_M = C_{MA} + m\beta\lambda_1 + nC_{p\sigma} \qquad (8.4)$$

so that

$$C_{MS} = m\beta\lambda_1 + nC_{p\sigma} \qquad (8.5)$$

where m and n are functions of E only and are plotted in Fig. 2.

Using the values of λ_1 and $C_{p\sigma}$ given by Eqns. (7.7) and (7.10), the predicted values of C_{MS} were found in the mean to be 6% greater than the experimental values, regardless of the spoiler position. This error of 6% is the same as that found for trailing edge spoilers.

The final expression for C_{MS} suggested for use with two-dimensional spoilers may thus be written as

$$C_{MS} = 0.94(m\beta\lambda_1 + nC_{p\sigma}) \qquad (8.6)$$

The values of C_{MS} obtained using Eqn. (8.6) are plotted in Fig. 21 together with the corresponding experimental values. The agreement is very satisfactory for spoilers at E = 0.89 and 0.71 and fair for E = 0.49.

The mean discrepancy of 6% at each spoiler position, including the trailing edge, provides, in effect, some justification for re-writing the incidence-dependent terms of Woods' expressions for C_L and C_M for spoilers ahead of the trailing edge. It is apparent that these modifications introduced no increased or less systematic discrepancies compared with that in the predicted pitching moment due to the trailing edge spoilers, for which such modifications were not required.

It should of course be noted that the values of $C_{p\sigma}$ determined using Eqn. (7.10) were adequate when used in predicting both C_{LS} and C_{MS}.

9. Further Experiments on Two-Dimensional Spoilers

A further series of tests was carried out to provide a check upon the theory evolved for the lift and pitching moment due to two-dimensional spoilers.

A 7.8 in. chord RAE100, 9% thick, symmetrical aerofoil was used. This aerofoil was chosen in order to obtain a reasonable difference in shape, and hence pressure distribution, from that of the RAE102 12% thick section. The maximum thickness of the RAE100 aerofoil was at 27% chord whereas that of the RAE102 was at 36% chord[20].

An uncambered aerofoil was used since it was considered that having decided upon a thinner section, the addition of camber would have the effect of returning the upper surface shape towards that of the RAE102 aerofoil.

The experimental arrangement was substantially the same as for the RAE102 balance model.

Two series of tests were made at speeds of 101 ft/sec and 50 ft/sec giving $R = 4.3 \times 10^5$ and 2.1×10^5 respectively.

Boundary layer traverses were carried out on the upper surface at both speeds and the values of the ratio $\frac{\delta^*}{c}$ at the values of E and α used are noted in Table 6.

Lift, drag and pitching moment measurements at both speeds, with $\alpha = 2°$ and $6°$, were made for the clean aerofoil, and for the aerofoil fitted with spoilers, with the spoiler positions and heights noted in Tables 2 and 3. The results obtained were corrected for tunnel interference by interpolating correction factors from those obtained for spoilers on the RAE102 balance model.

9.1 Comparison between experiment and theory

The values of the incremental lift coefficients due to two-dimensional spoilers on the RAE100 aerofoil at $E = 0.75$ and 0.9 are plotted in Figs. 22 and 23 for $R = 4.3 \times 10^5$ and 2.1×10^5 respectively. The agreement between the experimental values and the incremental lift coefficients predicted using the modified theory is very satisfactory.

The values of the incremental pitching moment coefficients due to two-dimensional spoilers on the RAE100 aerofoil are plotted in Fig. 24 for the range of values of α and R employed. Once again there is very satisfactory agreement between experiment and the predictions of the modified theory.

These results suggest that the modified theory is adequate for the prediction of the incremental lift and pitching moment coefficients due to unswept, two-dimensional spoilers normal to the upper surface of aerofoils in incompressible flow.

The two Reynolds numbers were sufficiently different to lead to reasonably different developments of boundary layer thickness (Table 6) and hence to slightly different values of the incremental coefficients due to a given spoiler at given E and α. The modified theory was adequate to predict such differences in incremental coefficients.

It is clear that the difference in shape between the RAE100 and RAE102 aerofoils has been adequately accounted for by the use of the parameters $\frac{\delta^*}{h}$ and $\frac{b}{c}$.

10. Incremental Drag Coefficient

Any method for predicting the incremental drag coefficient must take into account the aerofoil shape unless that part of the drag increment on the aerofoil itself is negligible compared with the force on the spoiler. Woods assumed this to be so (Section 3.2.2) but the experimental pressure distributions obtained in this investigation revealed that such an assumption is invalid, at least for $\frac{h}{c} \leqslant 0.1$.

It is not possible to obtain the chordwise force on the aerofoil by integrating the theoretical pressure distributions over the aerofoil surface since the term C_{pw} is not known.

Experimental data only are therefore presented in Fig. 25, which illustrates the dependence of C_{DS} on E and α for each spoiler tested on the RAE102 balance model.

11. Spoilers of Finite Span

A series of tests on spoilers of finite span was carried out using the RAE102 balance model.

The geometry of the finite spoilers was similar to that of the two-dimensional spoilers. The trailing edge test position was not used, the spoilers being mounted at the three positions ahead of the trailing edge (Table 2). The heights and spans of the finite spoilers tested are given in Table 4.

In order to determine the maximum permissible span of a finite spoiler such that its pressure field should not be modified by the presence of the tunnel side-walls, end-plates of 18 s.w.g. sheet steel were fitted to the aerofoil. The plates were mounted 2 in. from the aerofoil tips. The pressure field was assumed not to be modified by the tunnel side-walls when no difference could be detected between the incremental force coefficients due to a spoiler, measured with and without the end-plates fitted.

For the maximum spoiler height of $\frac{h}{c} = 0.1$, the maximum permissible span was found to be about 10 in. or $\frac{s}{c} = 1.2$. This span was not exceeded for any of the spoilers.

Tunnel interference corrections to the measured incremental force coefficients were obtained from the known values of the corrections for the two-dimensional spoilers. The percentage correction to a measured force coefficient due to a given finite spoiler was determined from the percentage correction required to the corresponding force coefficient due to the two-dimensional spoiler of the same height, at the same chordwise position and at the same aerofoil incidence. The two corrections were assumed to be in the ratio of the spoiler frontal areas. Although this process could provide only approximate corrections, their magnitude was sufficiently small for the error introduced in the final force coefficient to be very small.

11.1 Definition of incremental force coefficients

Since the aerofoil was effectively of infinite span, it seemed logical to base the incremental force coefficients due to a spoiler upon an area associated with the spoiler. The area sc was used. The incremental force coefficients were then written as

$$\left.\begin{aligned} C_{LSS} &= \frac{L_S}{\frac{1}{2}\rho U^2 sc} \\ C_{MSS} &= \frac{M_S}{\frac{1}{2}\rho U^2 sc^2} \end{aligned}\right\} \quad (11.1)$$

where pitching moment was measured about the leading edge. The previously undefined symbols are included in the Notation.

The coefficients given in Eqns. (11.1) were defined in this form since when s becomes very large they should then become equal to the corresponding coefficients due to two-dimensional spoilers. It is thus convenient to express a given incremental force coefficient due to a finite spoiler, in terms of the corresponding coefficient due to the two-dimensional spoiler with the same values of $\frac{h}{c}$, E and α. The ratios

$$\frac{C_{LSS}}{C_{LS}} \quad \text{and} \quad \frac{C_{MSS}}{C_{MS}} ,$$

which may be considered as measures of the effectiveness of a finite spoiler compared with that of a two-dimensional spoiler, were chosen for this purpose. This method facilitates comparison between the effectiveness of spoilers of different heights or spans at different values of E and α.

The ratios above will be referred to as the lift and pitching moment effectiveness respectively of finite spoilers.

11.2 Results

As noted in Section 11.1, it is convenient to present the measured incremental force coefficients due to finite spoilers, in terms of those due to the corresponding two-dimensional spoilers. The measured incremental lift and pitching moments are presented in this way in Figs. 26 to 29 as functions of $\frac{s}{c}$ for the chosen chordwise positions and aerofoil incidences.

Since the measured lift and pitching moment increments due to the very small span spoilers were themselves very small, a fairly large error was introduced when computing C_{LSS} and C_{MSS}, since in both cases the span s of the spoiler appears in the denominator of the coefficient. An estimate of the maximum possible range of these errors, which are of course dependent upon $\frac{s}{c}$, is plotted against $\frac{s}{c}$ in each of the Figs. 26 to 29, to the same scale as the experimental curves.

Inspection of Figs. 26 to 29 reveals that a definite trend towards a value of unity with increasing $\frac{s}{c}$ can be observed to have commenced by $\frac{s}{c} = 0.8$ for all the spoilers, independent of $\frac{h}{c}$ and hence of $\frac{s}{h}$. It is somewhat surprising that this tendency of C_{LSS} and C_{MSS} towards the corresponding two-dimensional values, i.e. $\frac{C_{LSS}}{C_{LS}}$ and $\frac{C_{MSS}}{C_{MS}}$ tending to unity, is a function of $\frac{s}{c}$ rather than of the spoiler aspect ratio $\frac{s}{h}$.

Surface oil flow patterns showed that, as for two-dimensional spoilers, the flow behind the spoilers remained separated back to the aerofoil trailing edge in all cases except for spoilers of $\frac{h}{c} = 0.023$ and $\frac{s}{c} = 0.27$ and 0.45 at $E = 0.49$ and $\alpha = 0°$. In the latter two cases flow reattachment occurred upstream of the trailing edge.

11.3 Discussion of results

Inspection of Figs. 26 to 29 reveals immediately that the behaviour of finite spoilers is very complicated. It is clear that the dependence upon $\frac{s}{c}$ of the lift or pitching moment effectiveness can take very different forms for different values of $\frac{h}{c}$, E and α. For instance, it would be difficult to predict even the sign of a parameter such as $\frac{\partial}{\partial(\frac{s}{c})}\left(\frac{C_{LSS}}{C_{LS}}\right)$ over a wide range of $\frac{s}{c}$ at given values of $\frac{h}{c}$, E and α.

It must be emphasised, however, that plotting the effectiveness parameters rather than C_{LSS} or C_{MSS} alone, does tend to collapse the results and to reduce the apparent effect of changing α or E, particularly for the larger spans where $\frac{s}{c}$ is greater than about 0.8.

For example, comparison of the sets of curves for $\frac{C_{LSS}}{C_{LS}}$ for $E = 0.89$ and 0.71 for a given spoiler height shows that there is a marked similarity for $\frac{s}{c} > 0.8$. A similar comparison may be made for $\frac{C_{MSS}}{C_{MS}}$ No such comparison could be made if the effectiveness parameters were not based upon the two-dimensional coefficients.

The degree of collapse for spoilers at $E = 0.49$ was less, however, and in general spoilers at $E = 0.89$ and 0.71 behave rather more uniformly than those at $E = 0.49$. With decreasing E there is sometimes a tendency towards a reversal in sign of both the lift and pitching moment effectiveness.

The latter exhibits this tendency more frequently (Figs. 28(b) and 29(c)). A negative value for $\frac{C_{LSS}}{C_{LS}}$ was found only for the spoiler of height $\frac{h}{c} = 0.023$ and $\frac{s}{c} = 0.45$ at $E = 0.49$ and $\alpha = 0°$ where flow reattachment occurred on the aerofoil surface behind the spoiler. As noted in Section 11.2, the only other case of reattachment was for a spoiler of the same height and under the same conditions of E and α as that above but with $\frac{s}{c} = 0.27$. For this spoiler $\frac{C_{LSS}}{C_{LS}}$ was closely zero. Negative values of $\frac{C_{LSS}}{C_{LS}}$ of course imply a positive lift increment since all the measured values of C_{LS} were negative.

Such a reversal in sign of C_{LSS} would be highly undesirable in any spoiler installation upon an aircraft and it appears that small values of $\frac{s}{c}$ should be avoided in practice. However, there is no reason why reattachment should not occur for reasonably large values of $\frac{s}{c}$ if the corresponding value of $\frac{h}{c}$ is sufficiently small. Clearly the flow <u>must</u> reattach behind even a two-dimensional spoiler if its height becomes vanishingly small. It is possible that the lift increments due to spoilers of very small height would themselves be sufficiently small to be relatively insignificant, regardless of their sign, and a criterion based on spoiler span would be more important.

The results do suggest, however, that positive lift increments due to a finite spoiler on the upper surface are unlikely to occur unless there is reattachment behind the spoiler. It does not of course follow that such reattachment must always be associated with a positive lift increment. Maskell[21] attributes a much reduced lift increment due to a forward mounted 5% chord split flap, under some conditions, to reattachment behind the flap. No reversal in sign of the lift increment was experienced in that case, however.

It appears that parameters such as

$$\frac{\partial}{\partial(\frac{h}{c})} (C_{LSS})_{E,\, \frac{s}{c},\, \alpha} \quad \text{and} \quad \frac{\partial}{\partial(\frac{h}{c})} (C_{MSS})_{E,\, \frac{s}{c},\, \alpha}$$

are liable to reversal in sign either at very small values of $\frac{h}{c}$, or for very small values of $\frac{s}{c}$, or a combination of both factors. Such a reversal becomes more likely the further ahead of the trailing edge the spoiler is mounted. It seems that installations involving small span spoilers mounted far forward on the chord (ahead of 60% say), should be avoided.

The lift increments due to spoilers with very small values of $\frac{s}{c}$ are themselves very small, although C_{LSS} is defined in such a way as to be of the same order as C_{LS}. This is of course true of the pitching moment increments also. Such values of $\frac{s}{c}$ are therefore unlikely to be of practical importance unless a number of small spoilers are used in an array upon an aircraft.

It is clear that the lift and pitching moment effectiveness of small span spoilers, ($\frac{s}{c} < 0.8$ approximately), do not lend themselves to any simple method of prediction. Attempts to relate the force increments due to such small spoilers to those due to two-dimensional spoilers of the same height apparently have only a limited significance.

For longer spans the problems seem slightly more tractable and it is convenient to consider such spoilers separately.

11.3.1 Large span spoilers

Comparisons between the curves of lift and pitching moment effectiveness for spoilers of a given height at given α and E show that very considerable similarities exist for $\frac{s}{c} > 0.8$ and E = 0.89 and 0.71. Corresponding values of $\frac{C_{LSS}}{C_{LS}}$ and $\frac{C_{MSS}}{C_{MS}}$ are very nearly equal. The agreement between corresponding values of $\frac{C_{LSS}}{C_{LS}}$ and $\frac{C_{MSS}}{C_{MS}}$ at E = 0.49 is less good.

The definition of large span spoilers as having $\frac{s}{c} > 0.8$ was chosen on account of this correspondence, which may be written as

$$\frac{C_{LSS}}{C_{LS}} = \frac{C_{MSS}}{C_{MS}} \qquad (11.2)$$

at constant $\frac{h}{c}$, $\frac{s}{c}$, α and E and holds approximately for $\frac{s}{c} > 0.8$ and $E > 0.71$.

Eqn. (11.2) may of course be rearranged as

$$\frac{C_{MSS}}{C_{LSS}} = \frac{C_{MS}}{C_{LS}} \qquad (11.3)$$

which implies that the incremental centre of pressure due to a finite spoiler is at approximately the same position as that due to the corresponding two-dimensional spoiler, within the restricted range of $\frac{s}{c}$ and E noted above. This deduction from Eqn. (11.3) is strictly true at zero incidence only but the error introduced is small even at $\alpha = 8°$.

The values of $\frac{C_{MS}}{C_{LS}}$ can of course be satisfactorily determined using the modified theory developed in Sections 7 and 8.

Examination of general arrangement drawings of several current transport aircraft equipped with spoilers[22,23,24] shows that they conform to the criterion suggested earlier regarding spoiler position and span (p. 30) and that the range of $\frac{s}{c}$ and E employed is approximately in the region discussed here. It should be noted that the geometry of the aircraft spoilers described is by no means identical to that of the spoilers of this investigation, the latter being much simpler. In particular there are gaps between the spoiler sections on the aircraft which effectively reduce the total length of the spoilers and modify their behaviour.

Returning to the experimental results, it has not been considered worth while to ascribe an empirical value to $\frac{C_{LSS}}{C_{LS}}$ or $\frac{C_{MSS}}{C_{MS}}$ due to a spoiler in the range considered ($\frac{s}{c} > 0.8$, $E > 0.71$) but the dependence on α and E is sufficiently small to enable an estimate of these quantities to be made in conjunction with Figs. 26 to 29.

It seems that the lift or pitching moment effectiveness of such a spoiler could be estimated to within $\pm$ 15%. Equating the position of the incremental centre of pressure to that of the corresponding two-dimensional spoiler seems unlikely to introduce an error of greater than $\pm$ 3% of the aerofoil chord except for very small spoilers.

12. Comparison with Ailerons

This investigation was not intended primarily to provide information useful for comparing the relative merits of spoilers and conventional flap type ailerons. However, the position of the incremental centre of pressure due to a spoiler is of interest when considering the possibility of control reversal due to torsional flexure of the wing structure and may be compared with that due to typical ailerons.

It is demonstrated by Broadbent[25] that for the two-dimensional problem the reversal speed is proportional to the square root of the parameter

$$-\frac{a_2}{a_1 m_2}$$

where $a_1 = \left(\frac{\partial C_L}{\partial \alpha}\right)_\delta$, $a_2 = \left(\frac{\partial C_L}{\partial \delta}\right)_\alpha$ and $m_2 = \left(\frac{\partial C_M}{\partial \delta}\right)_\alpha$ and δ is a measure of control deflection. The negative sign arises since m_2 is normally of opposite sign to a_2 if nose-up pitching moments are taken as positive. (Reversal could not occur if they were of the same sign).

Rewriting the parameter above shows that the smallest possible value of

$$-a_1\left(\frac{\partial C_{MS}}{\partial C_{LS}}\right)_\alpha$$

is thus consistent with the maximum reversal speed, the suffix S indicating that it is the lift and pitching moment increments due to the spoiler which are important.

At small incidences $-\left(\frac{\partial C_{MS}}{\partial C_{LS}}\right)_\alpha$ is closely equal to the distance, expressed as a fraction of the aerofoil chord, of the incremental centre of pressure from the axis about which the pitching moment is measured, in this case the leading edge. The minimum value of

$$a_1 \cdot \frac{x_p}{c}$$

is thus required, where x_p is the distance from the leading edge to the incremental centre of pressure due to a spoiler. It should perhaps be noted that if the incremental centre of pressure due to a spoiler (or an aileron) lies ahead of the flexural axis then control reversal is not possible.

The range of values of $\frac{x_p}{c}$ obtained in this investigation is shown in Fig. 30 as a function of spoiler chordwise position for the two-dimensional spoilers. It is seen that the position of the incremental centre of pressure moves closer to the leading edge as E decreases.

Since the lift curve slope of an aerofoil fitted with a two-dimensional spoiler decreases as the spoiler moves closer to the leading edge (in the range $0.49 < E < 1.0$, Section 7.5) it is clear that the product $a_1 \cdot \frac{x_p}{c}$ decreases rapidly as E decreases and the control reversal speed rises correspondingly.

For spoilers aft of $E = 0.7$ the range plotted in Fig. 30 agrees well with the mean curve in Fig. 2A of the paper by Jones[5], reproduced from that by the Langley Research Staff[4]. Jones' approximate scale of centre of pressure location was derived using the relation

$$\left(\frac{\partial C_M}{\partial \alpha}\right)_{C_L} = a_1 \cdot \frac{x_p}{c}$$

and assuming a constant value of the lift curve slope a_1. The error introduced by this assumption is fairly small.

The incremental centre of pressure position for trailing edge spoilers also agrees well with the data of Voepel[12].

Comparison of the spoiler data with the mean curve for plain ailerons, also included in Jones' Fig. 2A, suggests that spoilers will give higher control reversal speeds than ailerons, except perhaps for spoilers very close to the trailing edge. For this case an aileron with hinge position ahead of about 85% chord would be superior, neglecting differences in lift curve slope.

It has been suggested[12] that the trailing edge provides the optimum location for spoilers, since the magnitude of the response time is then least and the possibility of flow reattachment on the aerofoil behind the spoiler is eliminated. The ratio of the lift increment to the drag increment due to a two-dimensional spoiler is greatest for trailing-edge spoilers[11].

The trailing edge is clearly the least favourable spoiler position in relation to control reversal, however. Also, the structural problems associated with stowing and actuating a spoiler in that region would be formidable.

13. Conclusions

This investigation must be considered as a first step towards a more comprehensive theory of spoilers.

It is suggested that the modified theory is adequate for the prediction of the incremental lift and pitching moment coefficients due to an unswept, two-dimensional spoiler normal to the upper surface of an aerofoil in incompressible flow. The success of the modified theory in predicting the effect of incidence on two aerofoils, of different sections, fitted with spoilers suggests that the theory will apply to a wide range of aerofoil shapes since a change of aerofoil incidence is similar in many respects to a change in aerofoil shape.

Some extension to finite spoilers was possible and this is summarised briefly in Section 13.3.

It may perhaps be useful to present concisely the modified two-dimensional spoiler theory and its range of application.

13.1 The modified theory for two-dimensional spoilers on aerofoils

The modified theory is presented here as the series of steps required to determine the lift and pitching moment increments due to a given spoiler at given values of E and α. It is assumed that the shape of the aerofoil is known.

The equation numbers previously allotted have been retained.

(a) Determine the boundary layer displacement thickness on the aerofoil at the required position and incidence in the absence of the spoiler. This may be done experimentally or by a calculation method.

(b) For the required spoiler height determine $\frac{\delta^*}{h}$.

(c) Evaluate

$$\frac{\bar{h}}{h} \cdot \frac{U_1}{U} = 1.22\,(0.1^{\frac{\delta^*}{h}}) \tag{7.3}$$

If preferred $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ may be read from Fig. 13.

(d) Determine λ_1 using

$$\lambda_1 = F\sqrt{\frac{2}{E + \sqrt{E}} \cdot \frac{h}{c} \cdot \frac{\bar{h}}{h} \cdot \frac{U_1}{U}}\,. \tag{7.7}$$

F is given in Fig. 1 as a function of the spoiler angle β for incompressible flow. Since the present theory was developed for normal spoilers it is not expected that it should apply to spoilers at other angles to the surface. For normal spoilers in incompressible flow $F = 1.06$.

(e) For spoilers ahead of the trailing edge find the base height parameter $\frac{b}{c}$ given by

$$\frac{b}{c} = (1 - E)\operatorname{Sin}\alpha + \frac{y_s}{c}\operatorname{Cos}\alpha + \frac{h}{c}\operatorname{Cos}(\alpha + \phi), \tag{7.8}$$

where

$$\operatorname{Tan}\phi = -\frac{dy}{dx}_{x=x_s}\,. \tag{7.9}$$

The shape of the aerofoil must be known to determine y_s and ϕ. Eqn. (7.8) applies only for normal spoilers on the upper surface.

(f) Using the value of $\frac{b}{c}$ determined above find $C_{p\sigma}$ from

$$C_{p\sigma} = 2\frac{b}{c} - 2.5\frac{h}{c} - 0.18. \qquad (7.10)$$

This is not necessary for trailing edge spoilers.

(g) Determine the incremental lift coefficient C_{LS} due to the spoiler from

$$C_{LS} = -\beta\lambda_1(\sqrt{E} + E) - \ell C_{p\sigma}\ , \qquad (7.6)$$

where ℓ is plotted as a function of E in Fig. 2. It is zero for spoilers at the trailing edge.

(h) Determine the incremental pitching moment coefficient C_{MS} due to the spoiler from

$$C_{MS} = 0.94(m\beta\lambda_1 + nC_{p\sigma}), \qquad (8.6)$$

where m and n are plotted as functions of E in Fig. 2. For trailing edge spoilers n is zero.

It should be noted that the restriction of β to $\frac{\pi}{2}$ radians applies also to Eqns. (7.6) and (8.6).

13.2 Range of validity of the modified theory

The range of parameters over which the modified theory was developed seems reasonably representative of practical conditions. The Reynolds number range of this investigation, $2.1 \times 10^5 < R < 4.3 \times 10^5$ is of course relatively low, however, and a check at higher values is desirable, although it is to be expected that the introduction of boundary layer parameters into the theory has been successful in allowing for such variations in scale.

The two-dimensional spoilers of this investigation were sufficiently tall to preclude flow reattachment on the aerofoil surface behind the spoiler and it seems fairly certain that the theory would break down for very small spoilers with flow reattachment on the aerofoil downstream. Wenzinger and Rogallo[26] found that spoilers of height $\frac{h}{c} < 0.02$ were relatively ineffective or of reversed effectiveness and they attributed this to reattachment on the aerofoil surface. There is at present no criterion for predicting the possibility of reattachment (except that it will occur only for very small spoilers).

Since spoilers have not been tested at positions ahead of $E = 0.49$ it is not to be expected that the modified theory would apply for spoilers ahead of this position. Similarly it is expected to apply only to spoilers normal to the aerofoil surface.

Eqn. (7.3) for $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ as a function of $\frac{\delta^*}{h}$ was developed for the range $0.065 \leq \frac{\delta^*}{h} \leq 1.06$ for trailing edge spoilers. It was afterwards used with success for spoilers ahead of the trailing edge and $\frac{\delta^*}{h}$ as slow as 0.023. It appears that in the range quoted above for trailing edge spoilers the error in $\frac{\bar{h}}{h} \cdot \frac{U_1}{U}$ is unlikely to be greater than ± 5% (Fig. 13). It should be noted that both C_{LS} and C_{MS} vary linearly as $\sqrt{\frac{\bar{h}}{h} \cdot \frac{U_1}{U}}$ and errors are thus reduced.

The expression for $C_{p\sigma}$, Eqn. (7.10), was determined for ranges of $\frac{b}{c}$ and $\frac{h}{c}$ of

$$0.03 \leq \frac{b}{c} \leq 0.224 \quad \text{and} \quad 0.023 \leq \frac{h}{c} \leq 0.1 .$$

The upper limits quoted are unlikely to be exceeded in practice except perhaps that for $\frac{b}{c}$ at large angles of incidence. Very small spoilers close to the trailing edge could have smaller values of $\frac{b}{c}$ than the minimum quoted above. The associated value of $\frac{h}{c}$ could of course be less than 0.023.

In the ranges considered it seems, in general, unlikely that errors in the prediction of $C_{p\sigma}$ would lead to errors greater than ± 0.03 in lift coefficient or ± 0.02 in pitching moment coefficient. For spoilers of height $\frac{h}{c} < 0.03$ far forward on the chord ($E = 0.49$ in this investigation) the errors will be slightly larger, possibly because reattachment on the aerofoil surface behind a spoiler becomes more likely as $\frac{h}{c}$ is decreased.

13.3 Finite spoilers on aerofoils

For a spoiler of span greater than $\frac{s}{c} = 0.8$ on the upper surface at $E \geq 0.7$ it should be assumed that the incremental centre of pressure due to the spoiler is at the same position on the aerofoil chord as that due to the two-dimensional spoiler of the same height and at the same values of E and α. For spoilers outside these restrictions it appears that the incremental centre of pressure will be ahead of that due to the corresponding two-dimensional spoiler.

The position of the incremental centre of pressure is given closely by the ratio $-\frac{C_{MS}}{C_{LS}}$, which can be determined using the modified theory.

It is suggested that spoilers should not be installed at positions on the chord ahead of $E = 0.6$ approximately, since it was found that the rate of change of spoiler lift increment with spoiler height may then be subject to reversal in sign, either for very small values of $\frac{h}{c}$ or for very small values of $\frac{s}{c}$, or a combination of both factors. A reversal in sign of the increment itself is also possible.

It should be remembered, however, that such far forward spoiler positions are unlikely to be used in practice on account of the associated response time[1,2].

13.4 Further factors requiring consideration

No investigation was made of the effect of varying the spoiler deflection angle but the Woods theory may be adequate to account for this approximately. Similarly, neither swept spoilers nor vented or perforated spoilers were considered.

The major step required is that of relating two-dimensional spoilers on aerofoils to spoilers on finite wings. The effects of wing planform are introduced and the parameters $\frac{h}{c}$, $\frac{s}{c}$, and $\frac{\delta^*}{h}$ are in general no longer constant along the spoiler span. A technique similar to that employed in the spoiler effectiveness theory of Jones et al.[10] might be useful in this respect.

It should of course be noted that the position of boundary layer transition, which was fixed in this investigation, may be affected by the deflection of a spoiler.

Acknowledgements

The author wishes to express his gratitude to Professor W.A. Mair for his generous advice and encouragement during the period of this investigation.

The author was in receipt of a maintenance grant from the Department of Scientific and Industrial Research.

References

No.	Author(s)	Title, etc.
1	Young, A. D.	Lateral control with high lift devices. A.R.C. R.& M.2583, May, 1941.
2	Kramer, M., Zobel, T. W. and Esche, C. G.	Lateral control by spoilers at the DVL. NACA TM-1307, August, 1951.
3	Prior, B. J.	BAC.111. Aerodynamic design. Aircraft Engineering, Vol.35, 1963, pp.149-152.
4	Langley Research Staff	Summary of lateral-control research. NACA Report 868, 1947.
5	Jones, G. W.	Review of current spoiler data. A.R.C.15 082, May, 1952.
6	Fischel, J. and Ivey, M. F.	Collection of test data for lateral control with full-span flaps. NACA TN-1404, 1948.
7	Pearcey, H. H. and Pankhurst, R. C.	Survey of progress in N.P.L. high-speed tunnel tests of spoilers on an aerofoil with 0.25c flap. A.R.C.15 291, October, 1952.
8	Pearcey, H. H., Pankhurst, R. C. and Lee, G. F.	Further results from N.P.L. high-speed tunnel tests of spoilers on an aerofoil with 0.25c flap: Interim note on small spoilers on the trailing edge of the deflected flap. A.R.C.15 415, November, 1952.
9	Franks, R. W.	The application of a simplified lifting-surface theory to the prediction of the rolling effectiveness of plain spoiler ailerons at subsonic speeds. NACA RM A54H26a, December, 1964.
10	Jones, A. L., Lamb, O. P. and Cronk, A. E.	A method for predicting lift effectiveness of spoilers at subsonic speeds. J. Aero. Sci., Vol.23, 1956.
11	Woods, L. C.	Theory of aerofoil spoilers. A.R.C. R.& M.2969, May, 1953.
12	Voepel, H.	German wind tunnel tests on trailing edge spoilers at subsonic and supersonic speeds. A.R.C.15 449, November, 1952.
13	Omori, Y.	Spoiler. J. of the Japan Society for Aeronautical and Space Sciences, Vol.11, No.108, 1963.
14	Woods, L. C.	The Theory of Subsonic Plane Flow. Cambridge University Press, 1961.
15	Nash, J. F.	A review of research on two-dimensional base flow. A.R.C. R.& M.3323, March, 1962.
16	Maskell, E. C.	A theory of the blockage effects on bluff bodies and stalled wings in a closed wind tunnel. A.R.C. R.& M.1566, November, 1963.

No.	Author(s)	Title, etc.
17	Glauert, H.	Wind tunnel interference on wings, bodies and airscrews. A.R.C. R.& M.1566, 1933.
18	Tanner, L. H., Pearcey, H. H. and Tracey, C. M.	Vortex generators; their design and their effects on turbulent boundary layers. Preliminary report. A.R.C.16 487, January, 1954.
19	Barnes, C. S.	Two-dimensional normal fences on a flat plate. A.R.C. C.P.863, February, 1965.
20	Pankhurst, R. C. and Squire, H. B.	Calculated pressure distributions for the RAE100-104 aerofoil section. A.R.C. C.P.80, March, 1950.
21	Maskell, E. C.	Pressure distributions illustrating flow reattachment behind a forward mounted flap. A.R.C. C.P.211, March, 1954.
22	Carline, A. J. K.	BAC.111. Basic design philosophy. Aircraft Engineering, Vol.35, 1963, pp.127-137, 140-141.
23	Aircraft Engineering	Short Belfast. Evolution and design philosophy. Aircraft Engineering, Vol.35, 1963, pp.250-252.
24	Hay, J. A.	Vickers VC.10. Aerodynamic design. Aircraft Engineering, Vol.34, 1962, pp.158-164.
25	Broadbent, E. G.	The Elementary Theory of Aero-Elasticity. Aircraft Engineering Monograph, Bunhill Publications Ltd., 1954.
26	Wenzinger, C. J. and Rogallo, F. M.	Wind-tunnel investigation of spoiler deflector, and slot lateral-control devices on wings with full-span split and slotted flaps. NACA Report 706, 1941.

$\frac{x}{c}$
0
0.01
0.03
0.05
0.07
0.10
0.14
0.173
0.24
0.30
0.36
0.42
0.46
0.49
0.52

$\frac{x}{c}$
0.55
0.58
0.61
0.64
0.67
0.70
0.73
0.76
0.79
0.82
0.85
0.88
0.91
0.94
0.97

$\frac{x}{c}$
0.01
0.03
0.05
0.07
0.10
0.14
0.173
0.24
0.30
0.40
0.49
0.58
0.67
0.76
0.85
0.91
0.95

Upper Surface

Lower Surface

Table 1. Pressure Tapping Positions on the RAE102 Aerofoil

Aerofoil	E
BOTH RAE102	0.49
	0.71
	0.89
	1.00
RAE100	0.75
	0.90

Table 2. Spoiler Test Positions on Aerofoils

Aerofoil	$\frac{h}{c}$
BOTH RAE102	0.023
	0.047
	0.100
RAE100	0.030
	0.070

Table 3. Heights of Spoilers Tested on Aerofoils

$\frac{h}{c}$	$\frac{s}{c}$
0.023	0.27
	0.45
	0.80
	1.13
0.047	0.19
	0.56
	0.80
	1.16
0.100	0.10
	0.20
	0.40
	0.80
	1.20

Table 4. Finite Span Spoilers

E	$\alpha°$	$\frac{\delta^*}{c}$
0.49	0	0.0023
	4	0.0025
	8	0.0051
0.71	0	0.0035
	4	0.0047
	8	0.0100
0.89	0	0.0052
	4	0.0077
	8	0.0172
1.0	0	0.0065
	4	0.0101
	8	0.0240

Table 5. Boundary Layer Displacement Thickness on the RAE102 Aerofoils

E	α°	R=4.3×10^5	R=2.1×10^5
		$\frac{\delta^*}{c}$	$\frac{\delta^*}{c}$
0.75	2	0.0049	0.0054
	6	0.0090	0.0103
0.9	2	0.0060	0.0067
	6	0.0109	0.0125

Table 6. Boundary Layer Displacement Thickness on the RAE100 Aerofoil

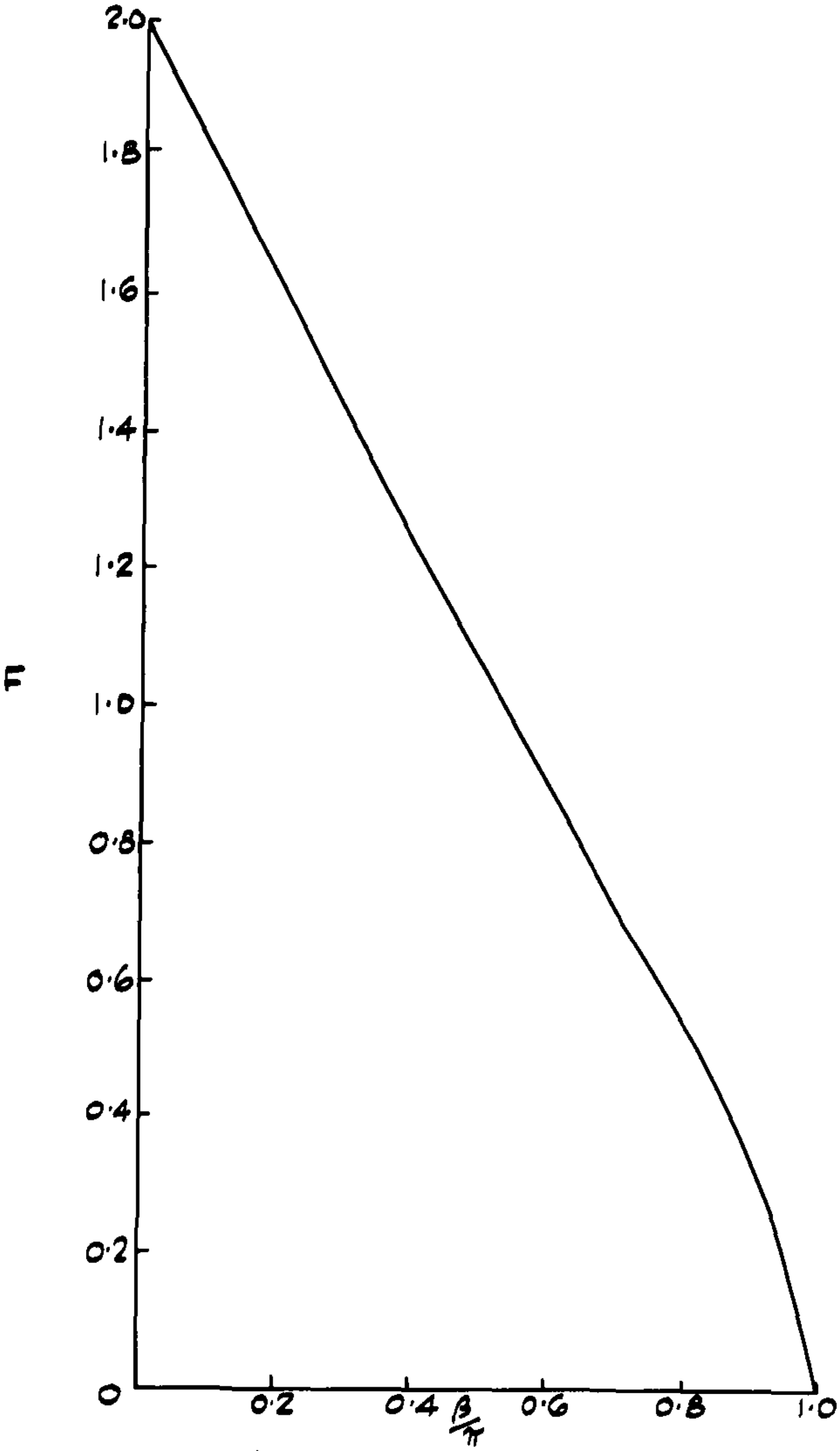


FIG. 1. WOODS' FUNCTION F IN INCOMPRESSIBLE FLOW

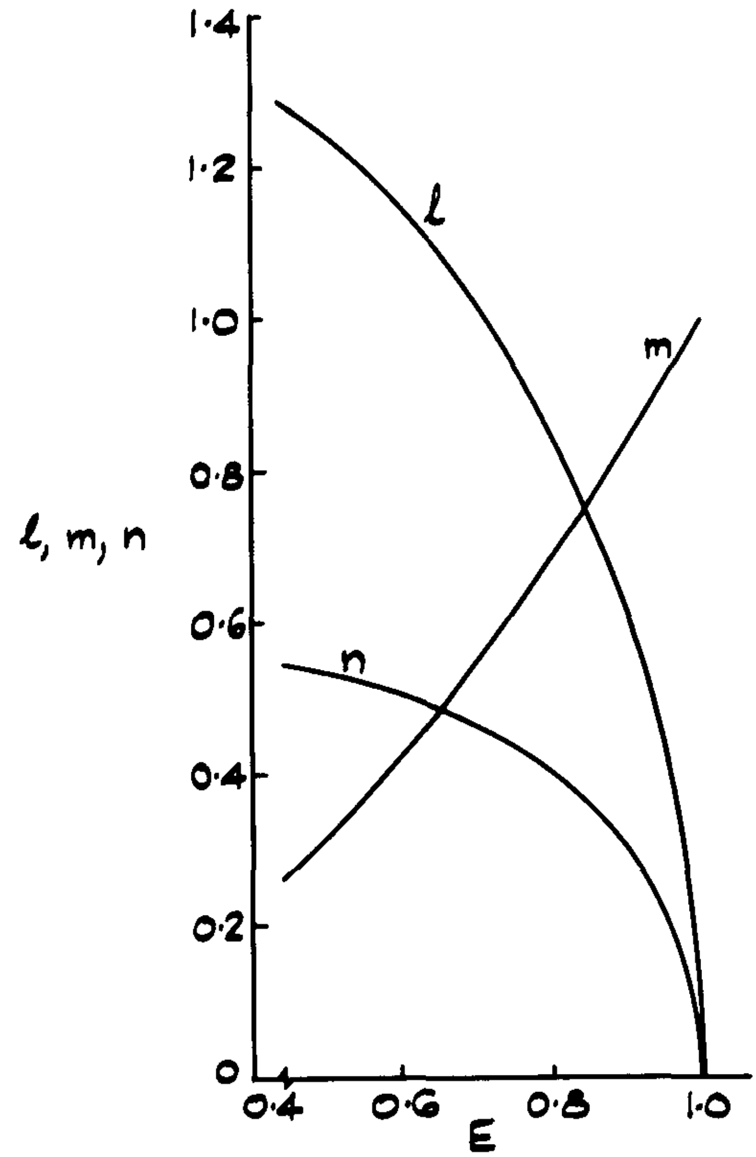
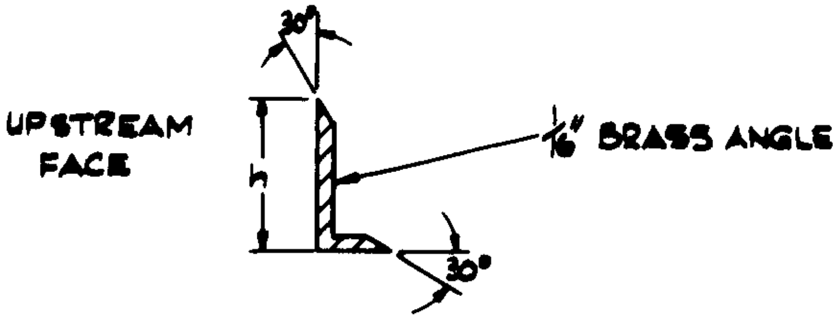
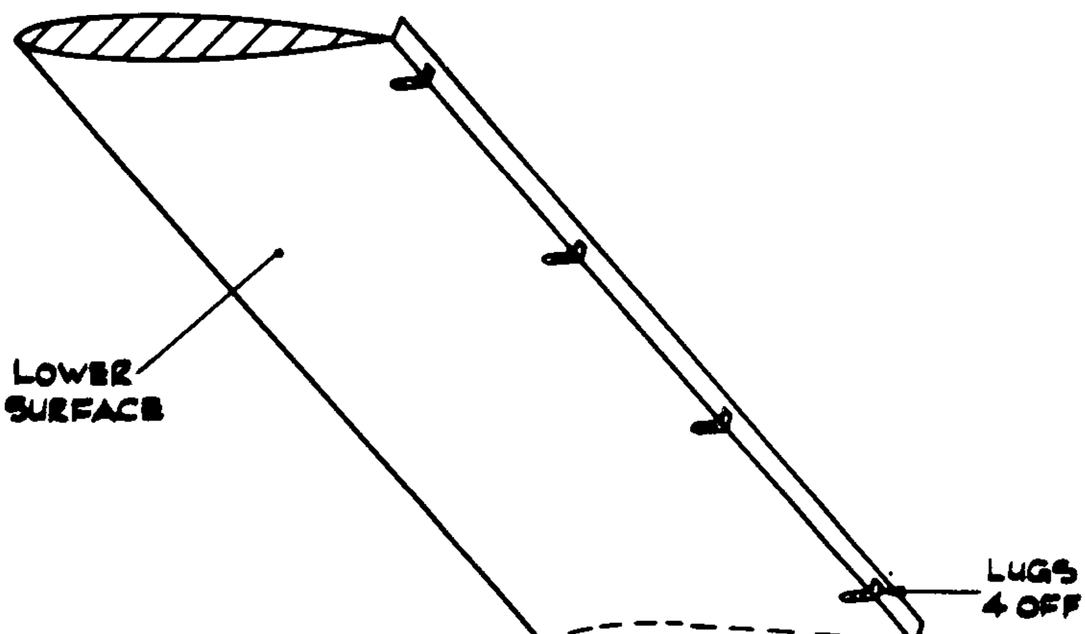


FIG. 2. DEPENDENCE OF l, m AND n UPON E



(a) SPOILERS AHEAD OF THE TRAILING EDGE



(b) TRAILING EDGE SPOILER INSTALLATION

FIG. 3. GEOMETRY OF SPOILERS ON AEROFOILS

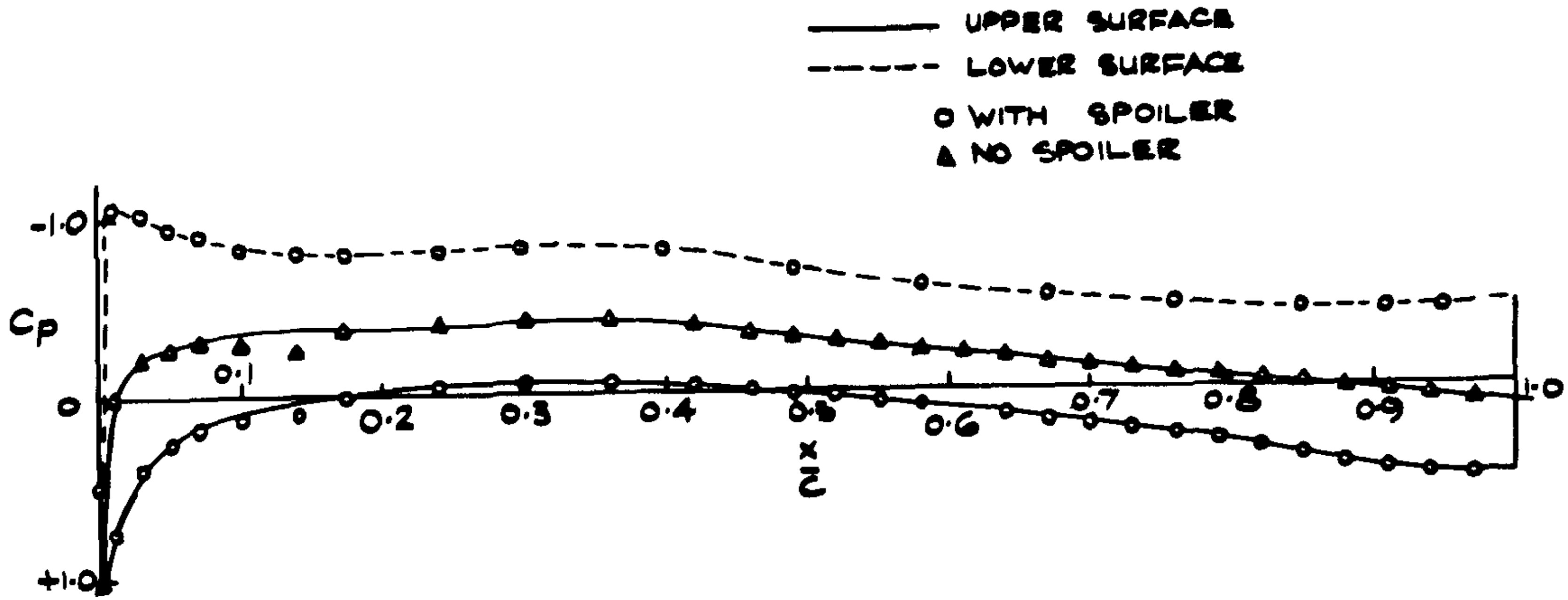


FIG. 4. PRESSURE DISTRIBUTIONS $\frac{h}{c} = \cdot 047$ AND 0, $E = 1\cdot 0$, $\alpha = 0°$

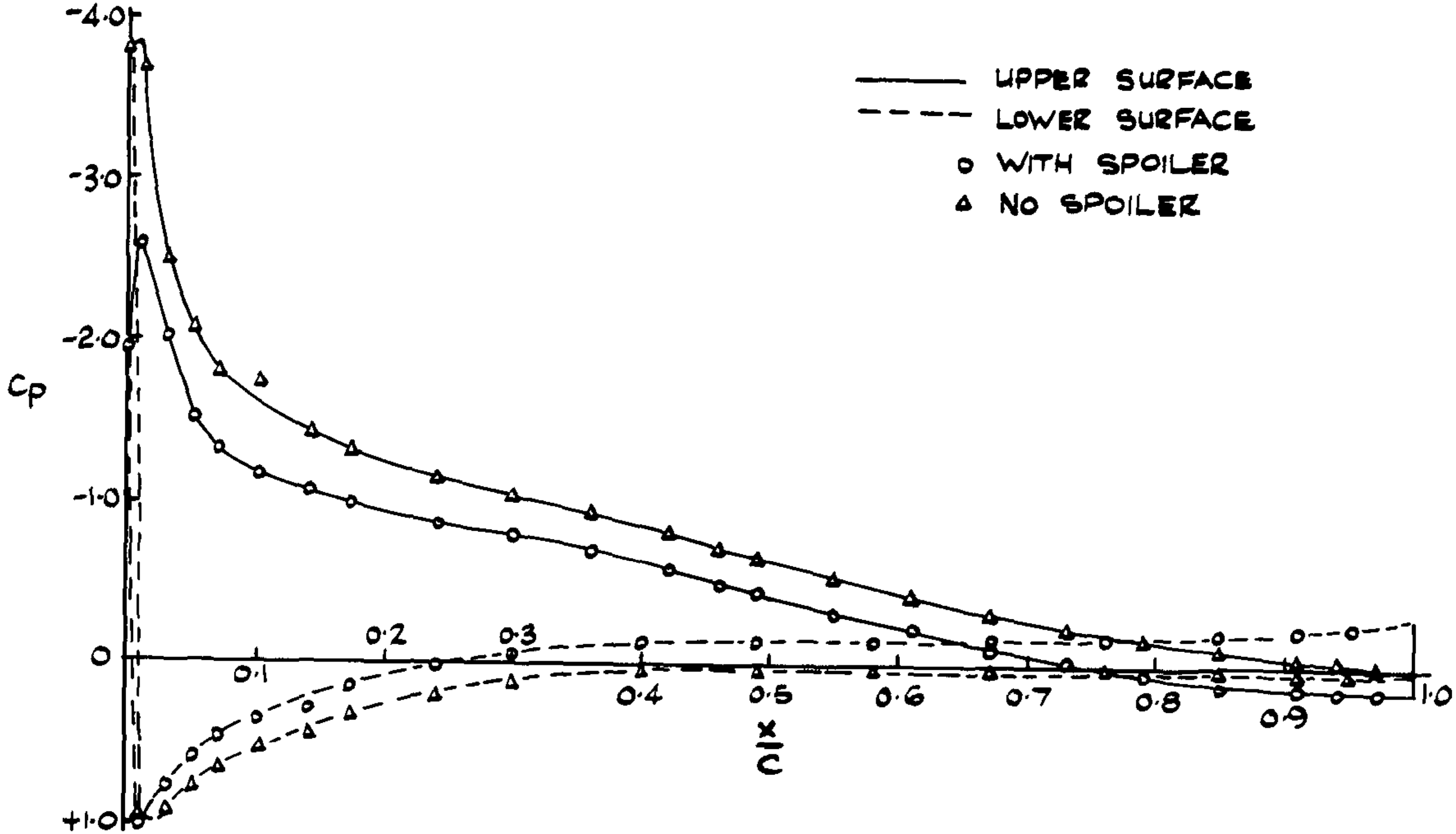


FIG. 5. PRESSURE DISTRIBUTIONS $\frac{h}{c} = \cdot 047$ AND 0, $E = 1\cdot 0$, $\alpha = 8°$

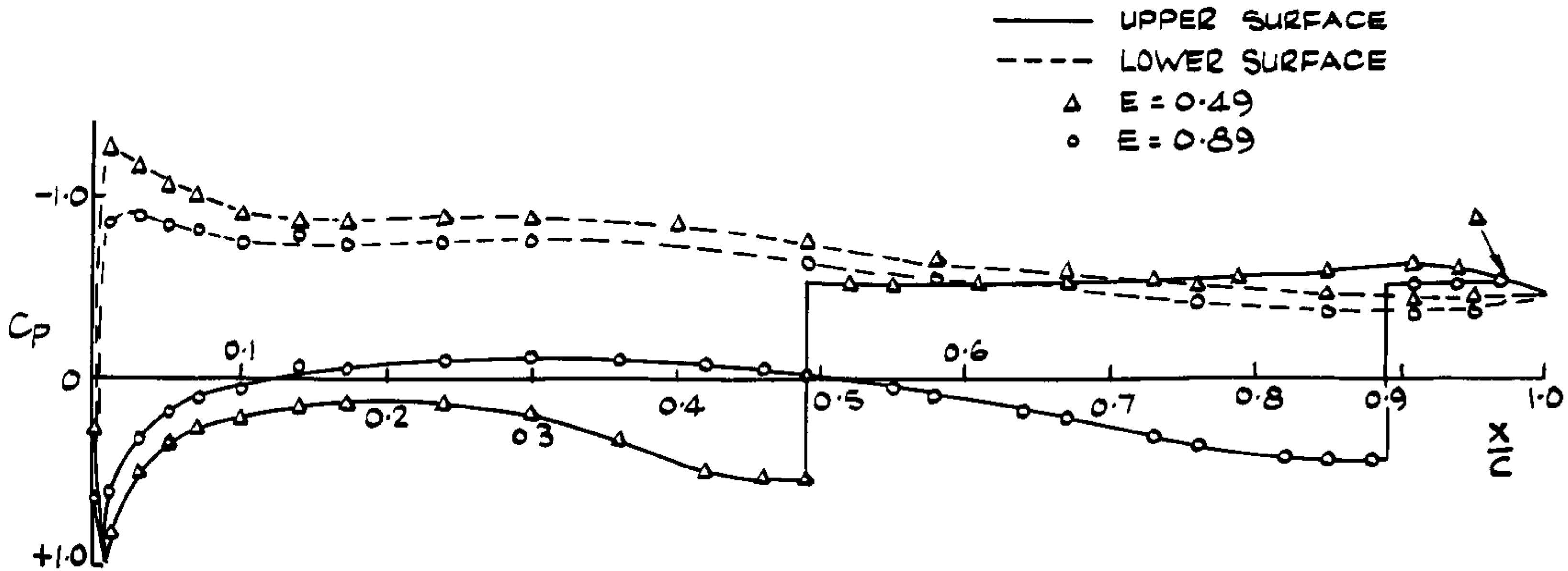


FIG. 6. PRESSURE DISTRIBUTIONS $\frac{h}{c} = \cdot 047$, $E = 0{\cdot}49$ AND $0{\cdot}89$, $\alpha = 0°$

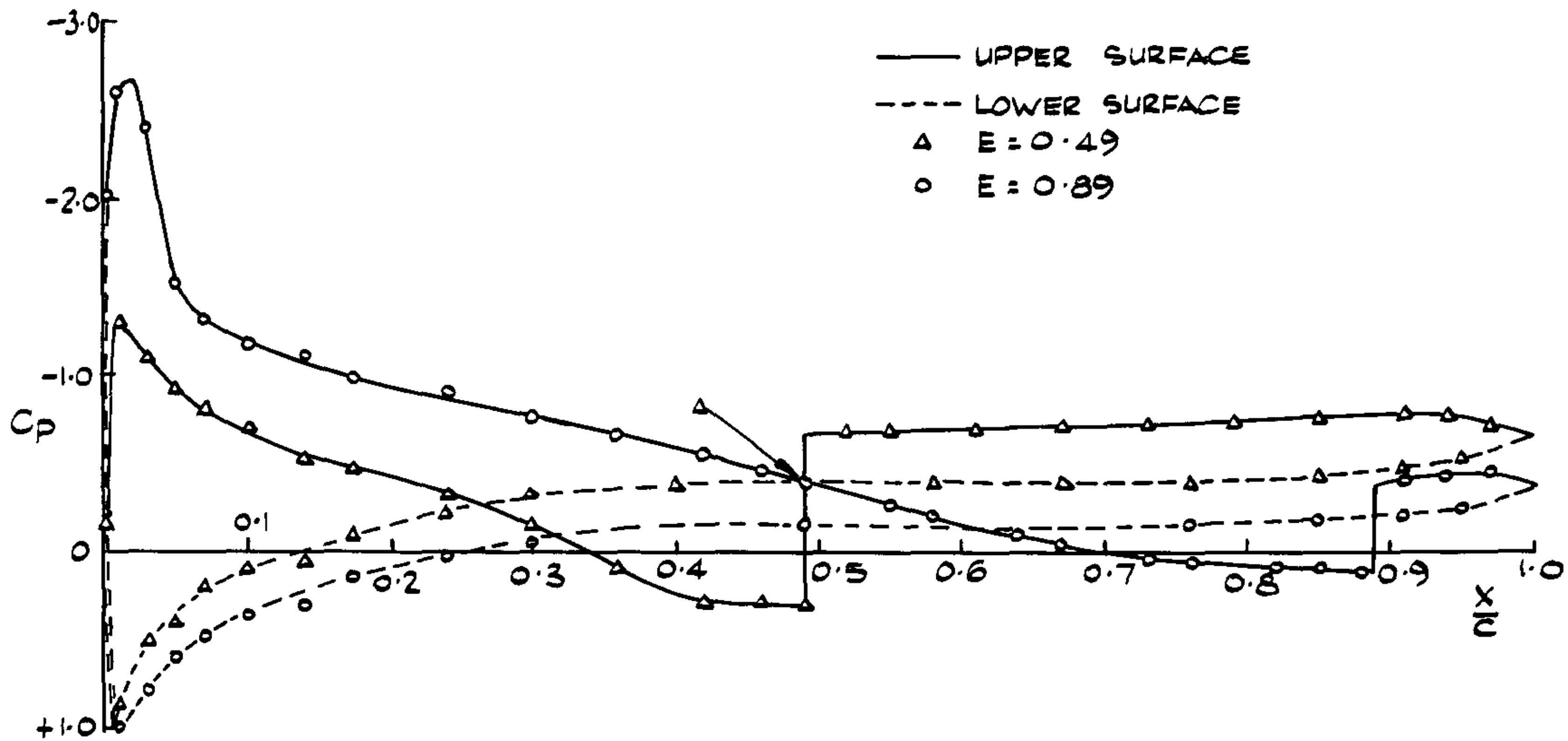


FIG. 7. PRESSURE DISTRIBUTIONS $\frac{h}{c} = \cdot047$, E = 0·49 AND 0·89, $\alpha = 8°$

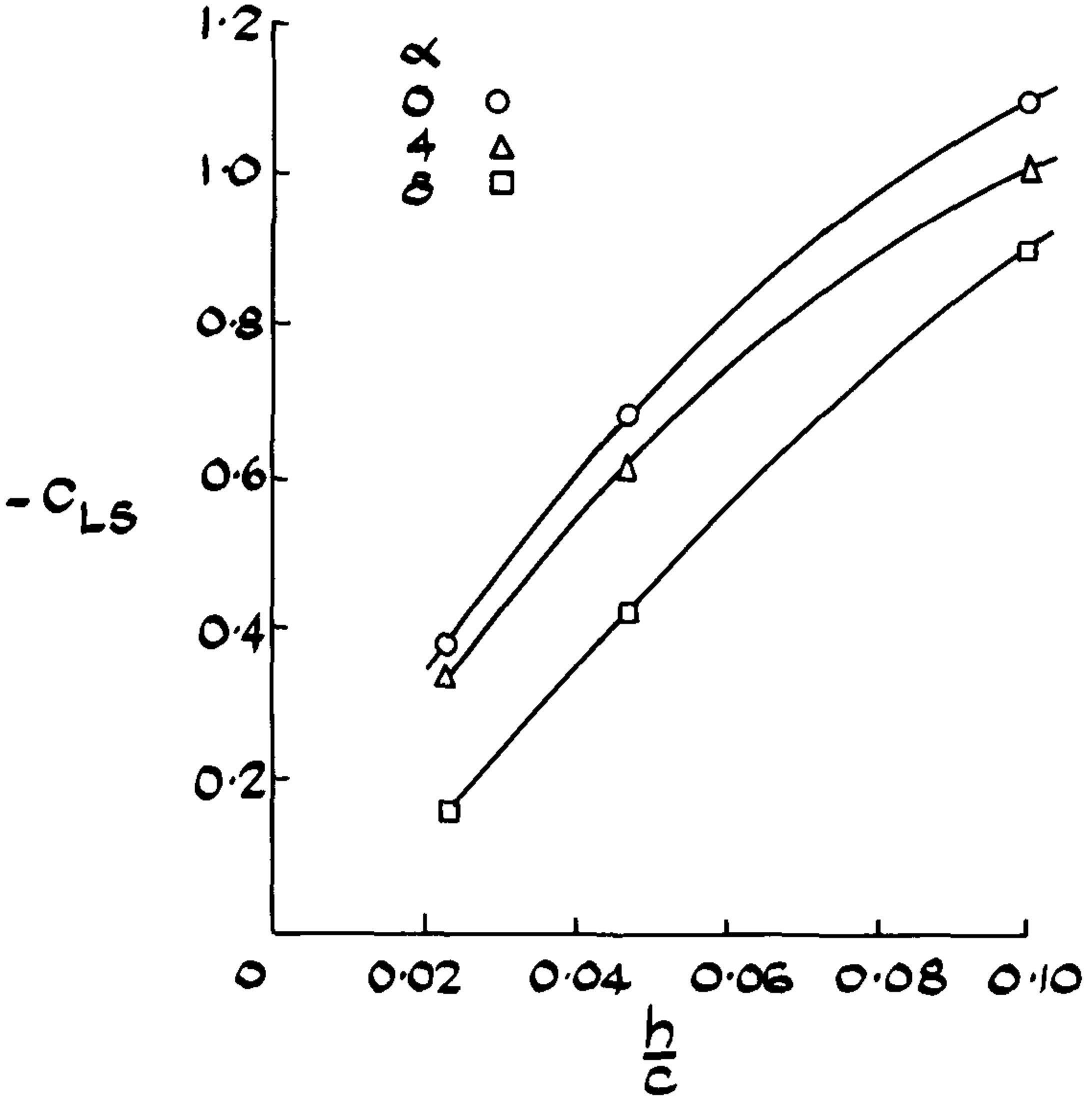


Fig. 8 INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL TRAILING EDGE SPOILERS ON AN RAE 102 AEROFOIL

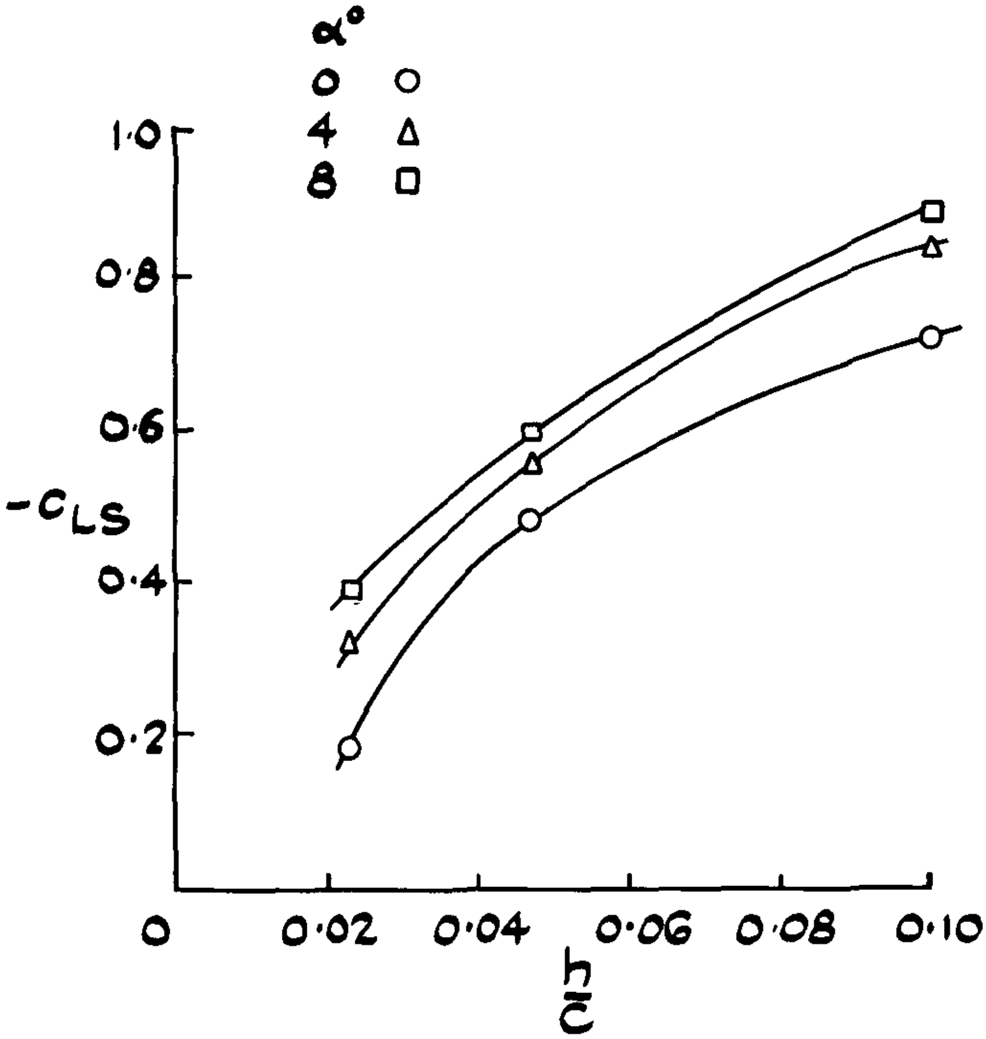


Fig.9. INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS AT E = 0·49 ON AN RAE 102 AEROFOIL

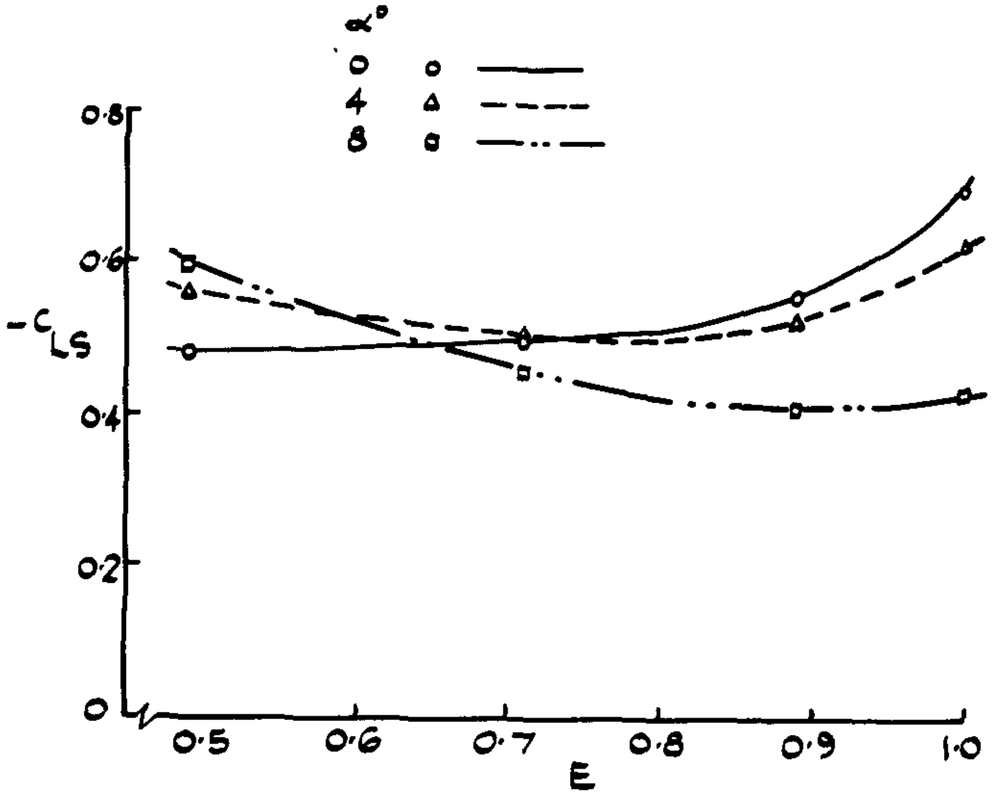


FIG. 10. DEPENDENCE ON α AND E OF THE INCREMENTAL LIFT COEFFICIENTS DUE TO A TWO-DIMENSIONAL SPOILER OF $\frac{h}{c} = \cdot 047$ ON AN RAE 102 AEROFOIL

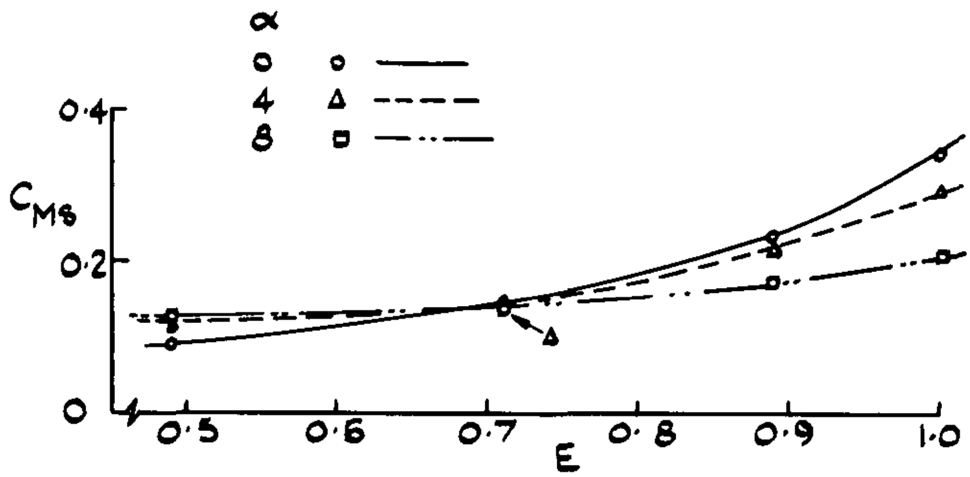


FIG. 11. DEPENDENCE ON α AND E OF THE INCREMENTAL PITCHING MOMENT COEFFICIENTS DUE TO A TWO-DIMENSIONAL SPOILER OF $\frac{h}{c} = \cdot 047$ ON AN RAE 102 AEROFOIL

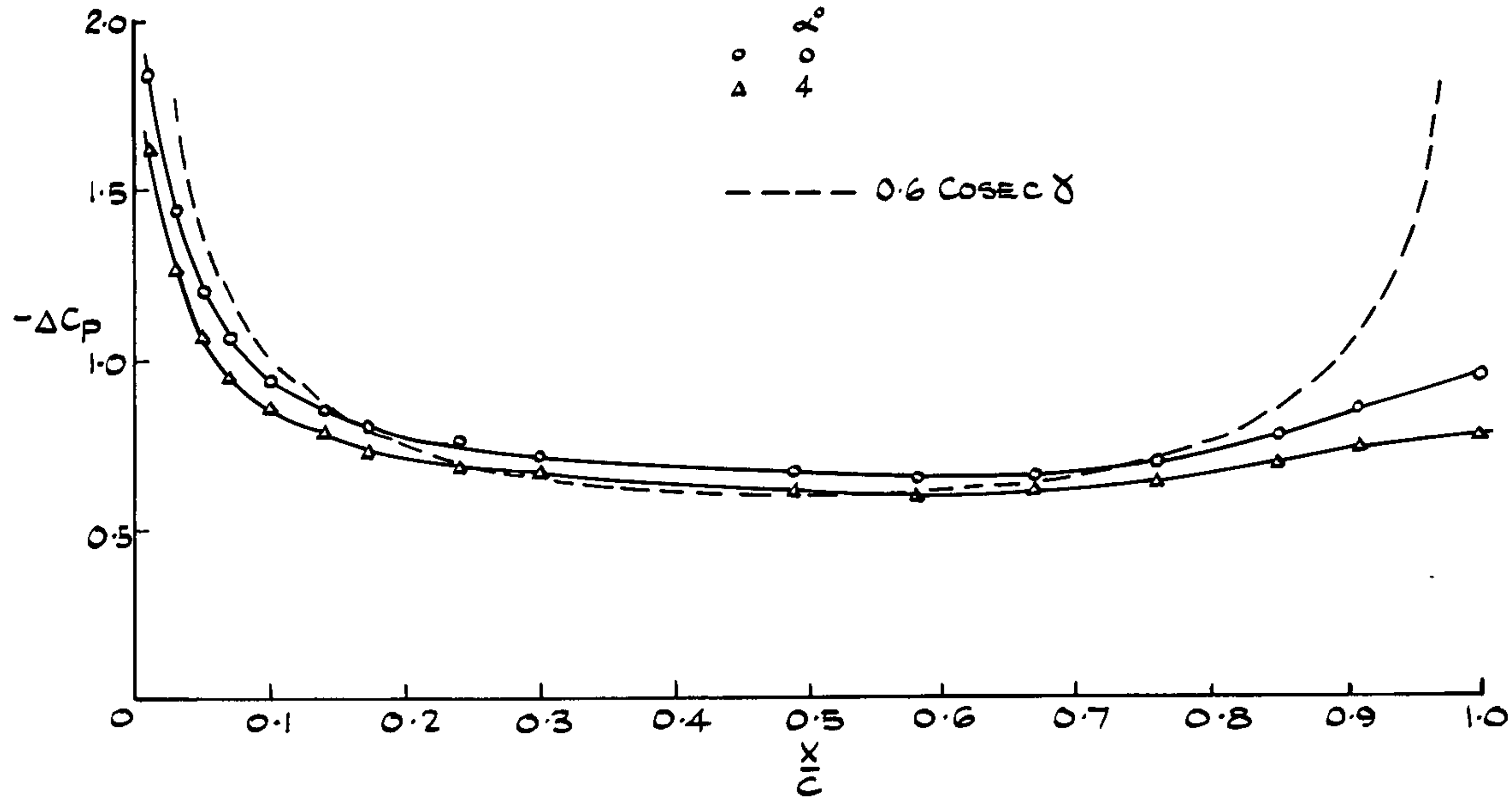


FIG. 12. INCREMENTAL LOAD COEFFICIENT DISTRIBUTIONS

$\frac{h}{c} = \cdot 047$, $E = 1$, $\alpha = 0°$ AND $4°$

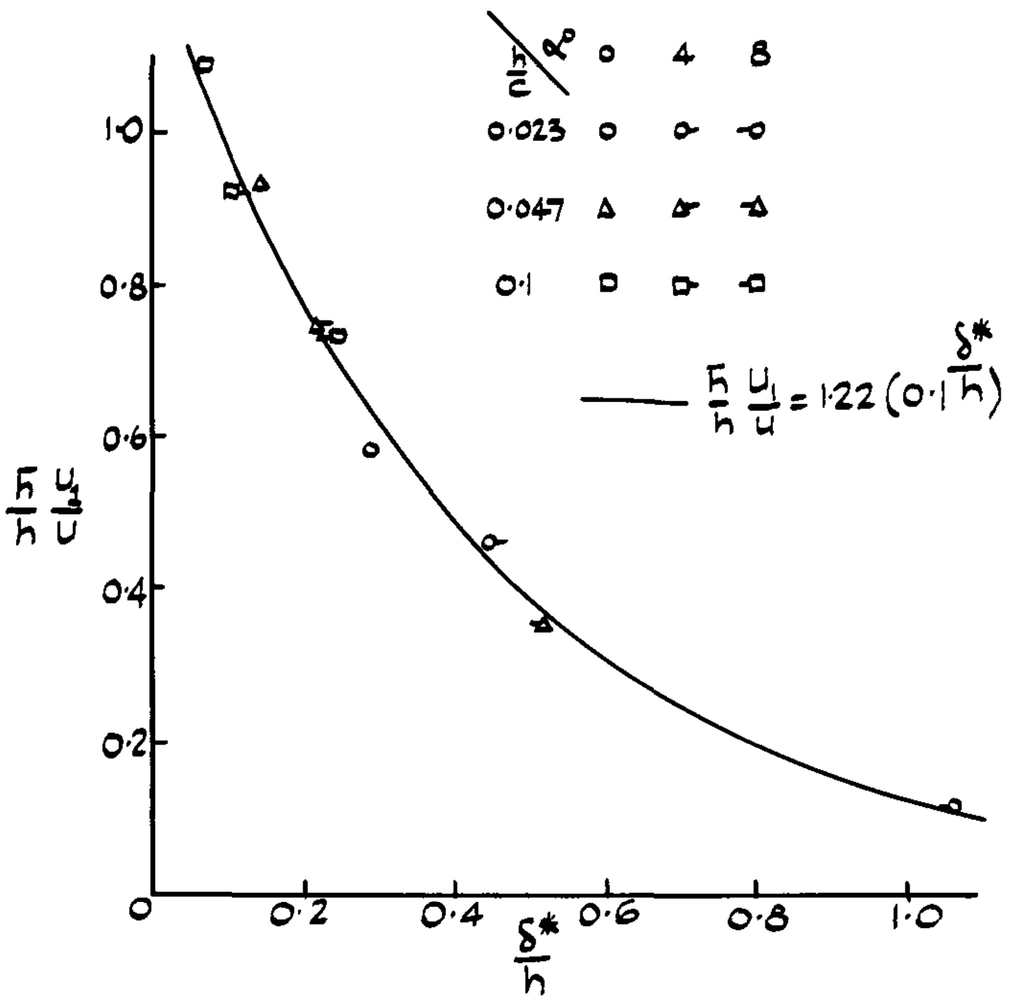


FIG. 13. DEPENDENCE OF $\frac{\bar{h}}{h}\frac{U_1}{U}$ UPON $\frac{\delta^*}{h}$ FOR TWO-DIMENSIONAL TRAILING EDGE SPOILERS

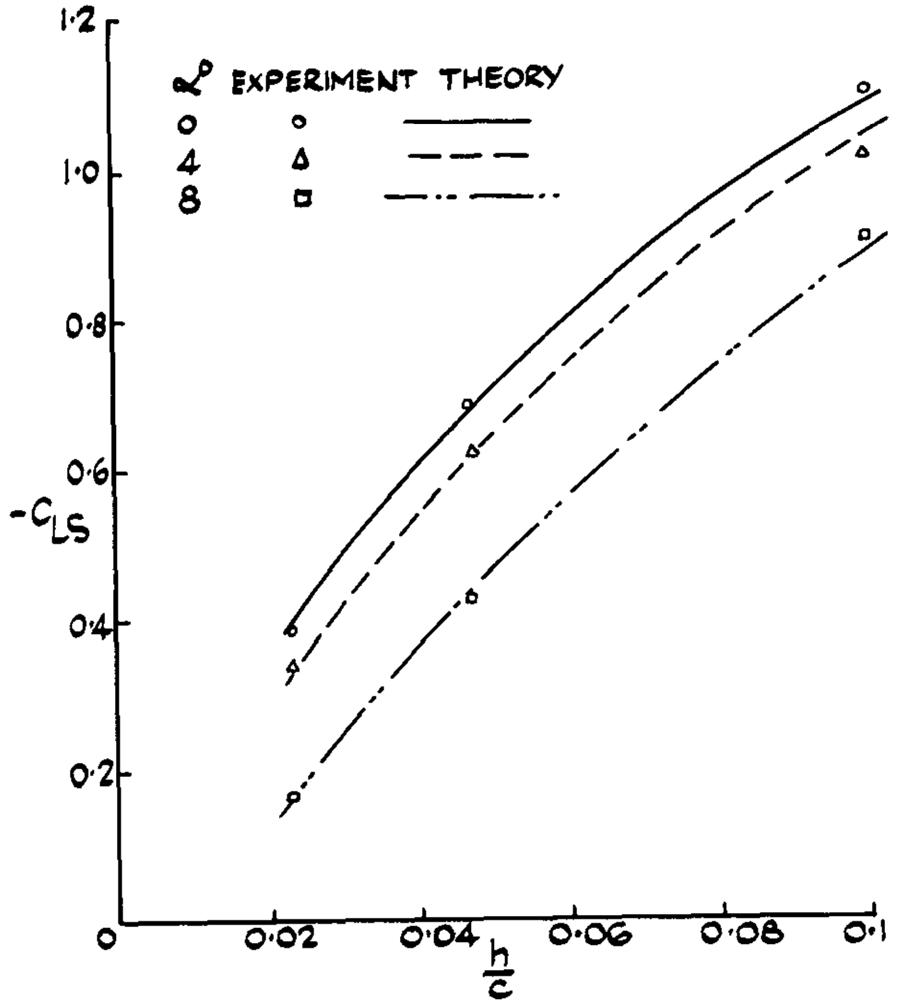
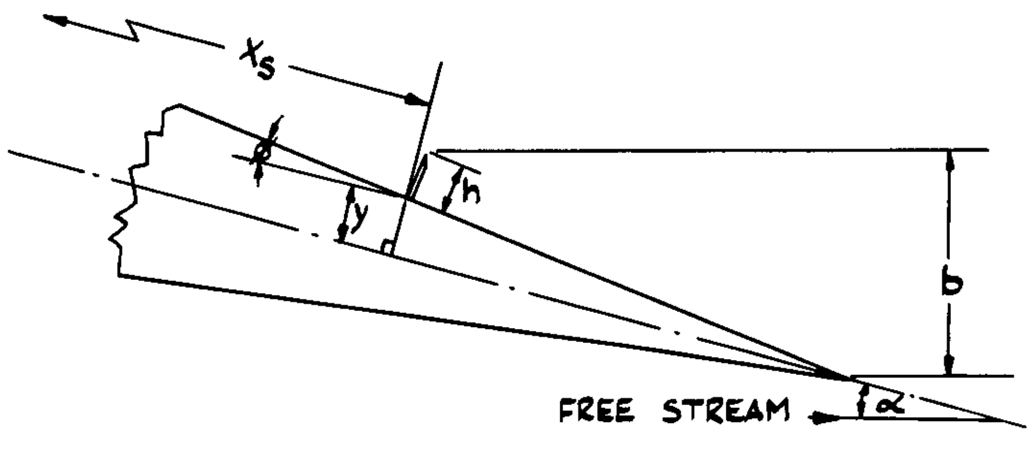


FIG. 14. INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL TRAILING EDGE SPOILERS ON AN RAE 102 AEROFOIL



$$\frac{b}{c} = (1-E)\sin\alpha + \frac{y}{c}\cos\alpha + \frac{h}{c}\cos(\alpha+\phi)$$

FIG. 15. EFFECTIVE BASE HEIGHT, b.

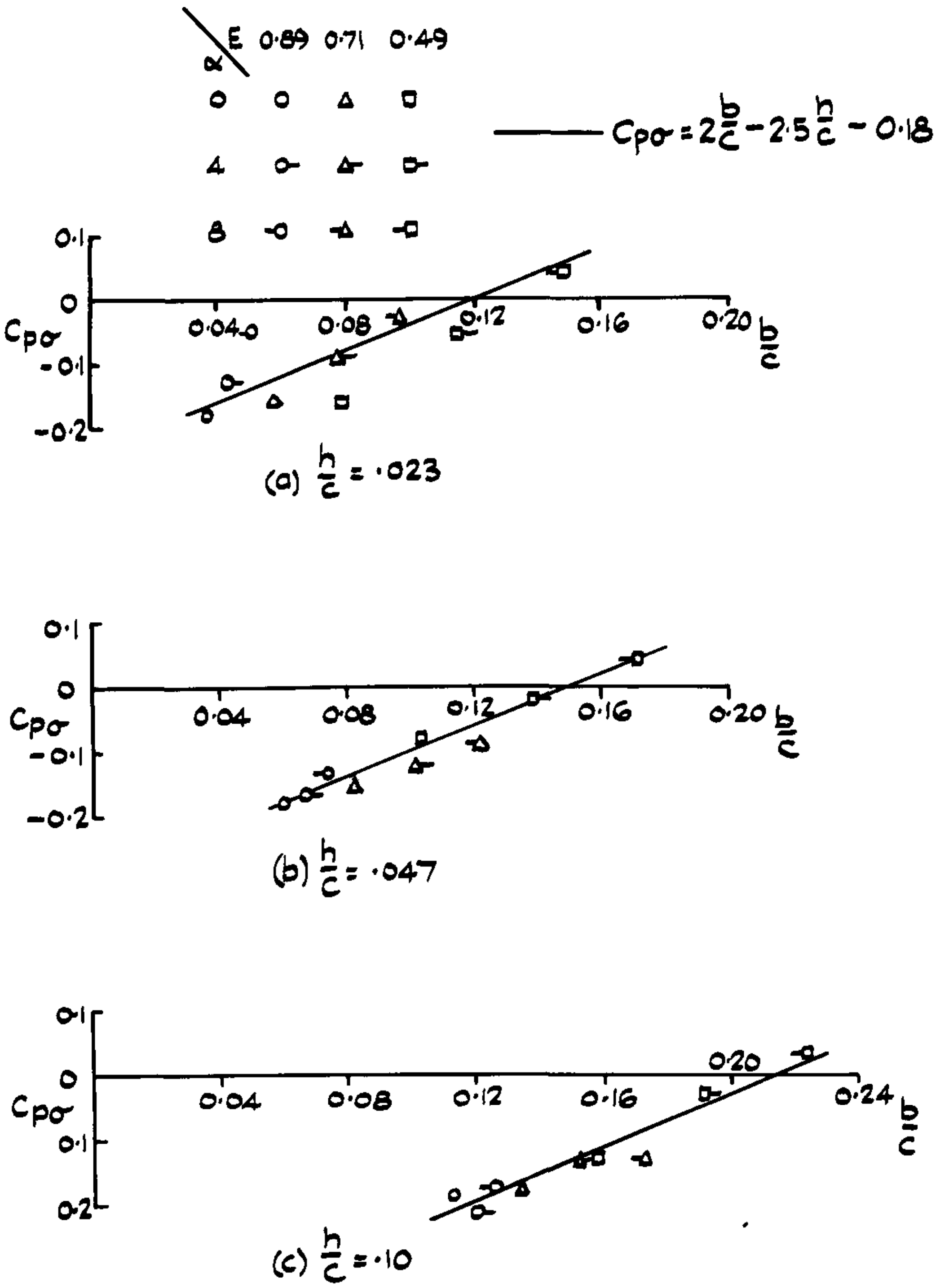


FIG. 16. DEPENDENCE OF $C_{p\sigma}$ ON $\frac{b}{c}$ AND $\frac{h}{c}$

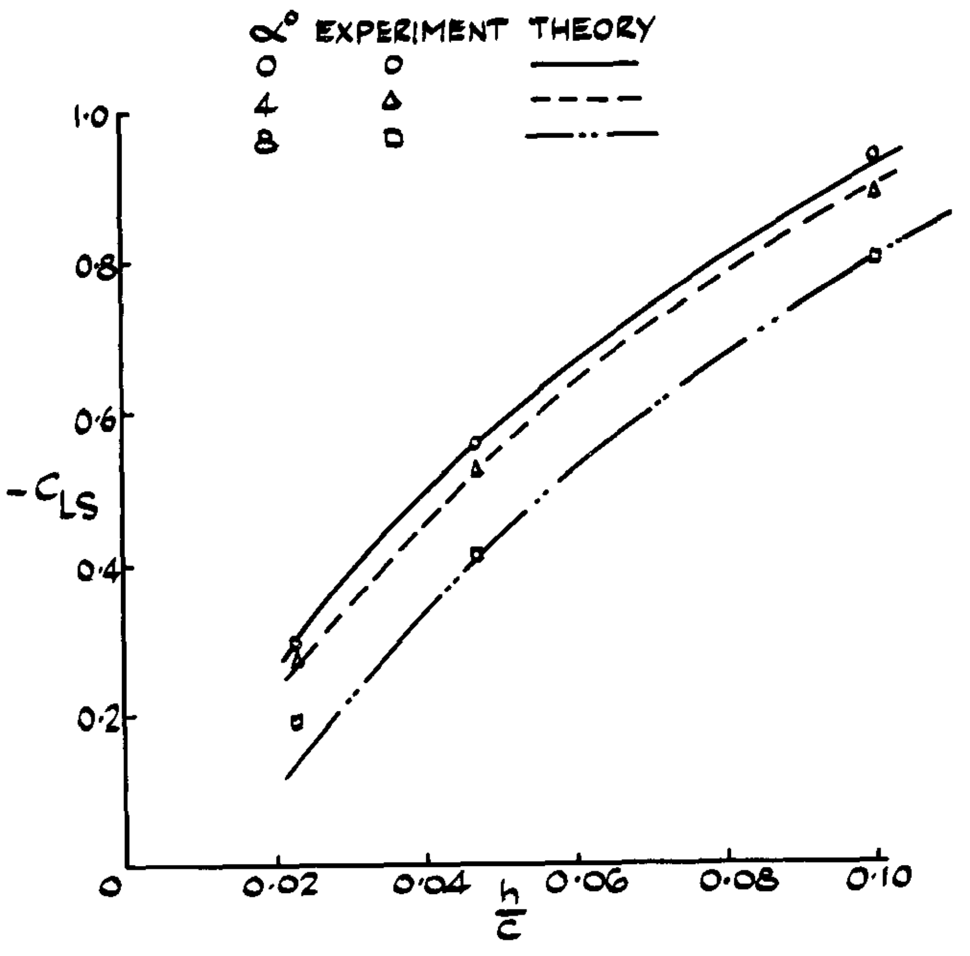


FIG. 17. INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS AT E=0·89 ON AN RAE102 AEROFOIL

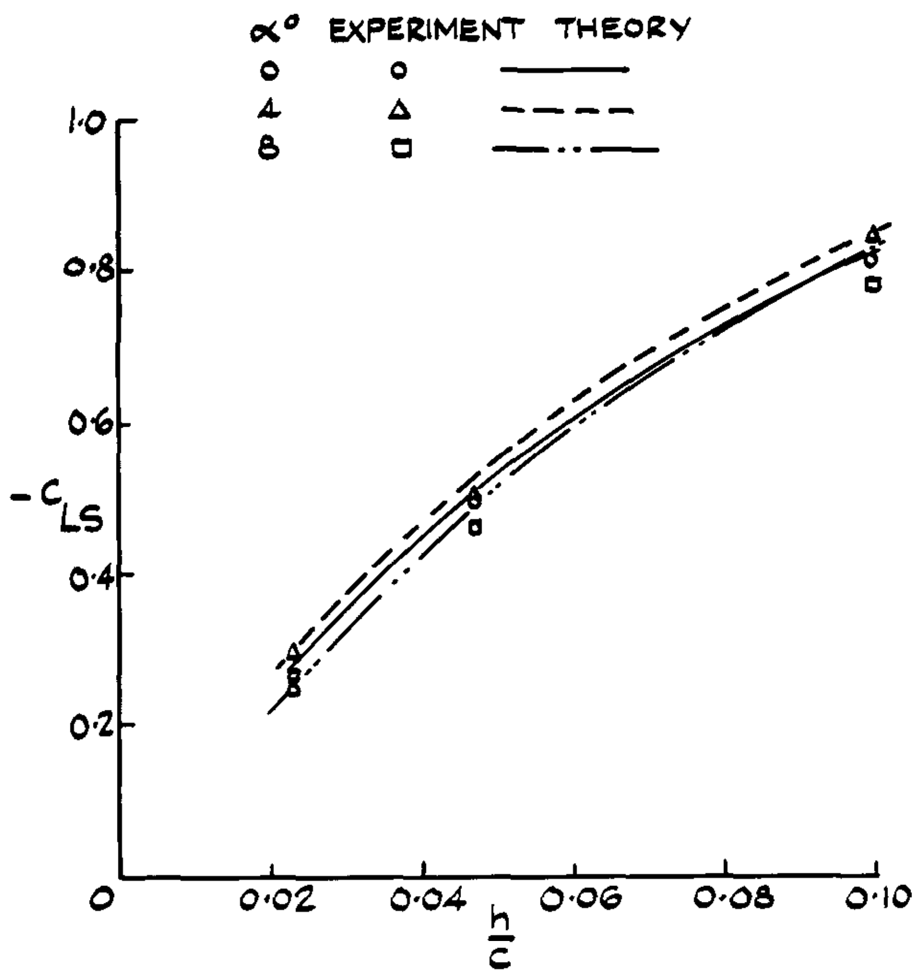


FIG. 18. INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS AT E=0·71 ON AN RAE 102 AEROFOIL

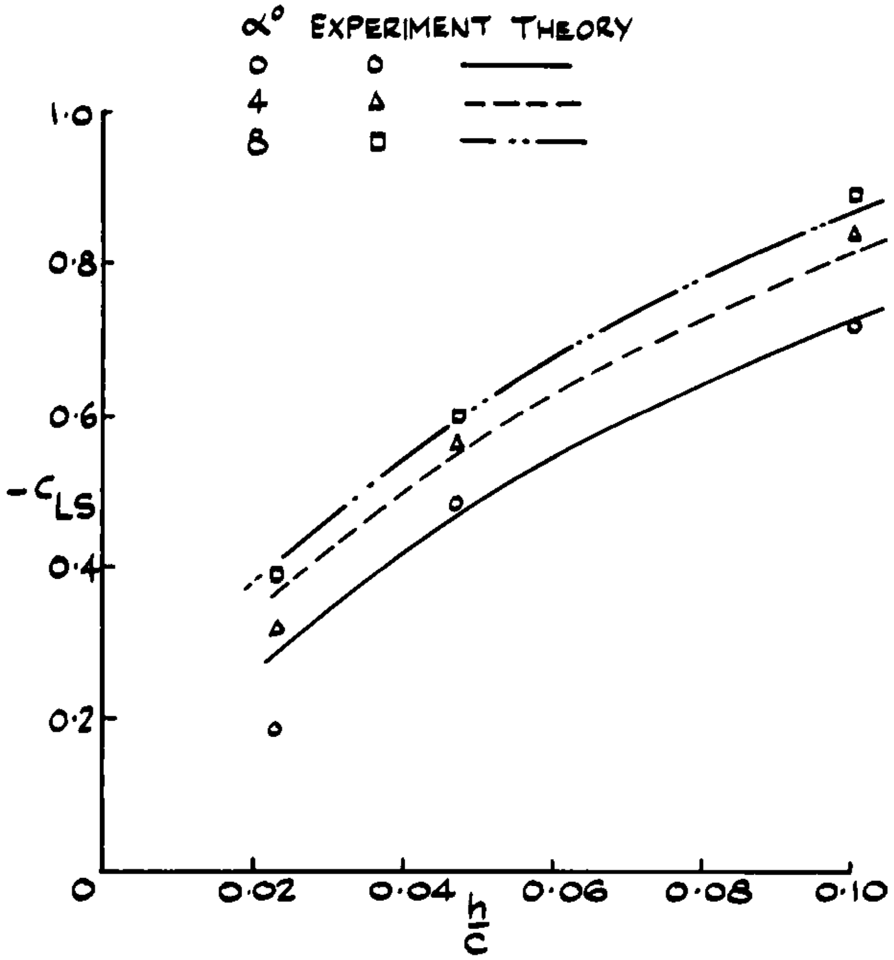


FIG. 19. INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS AT E = 0·49 ON AN RAE 102 AEROFOIL

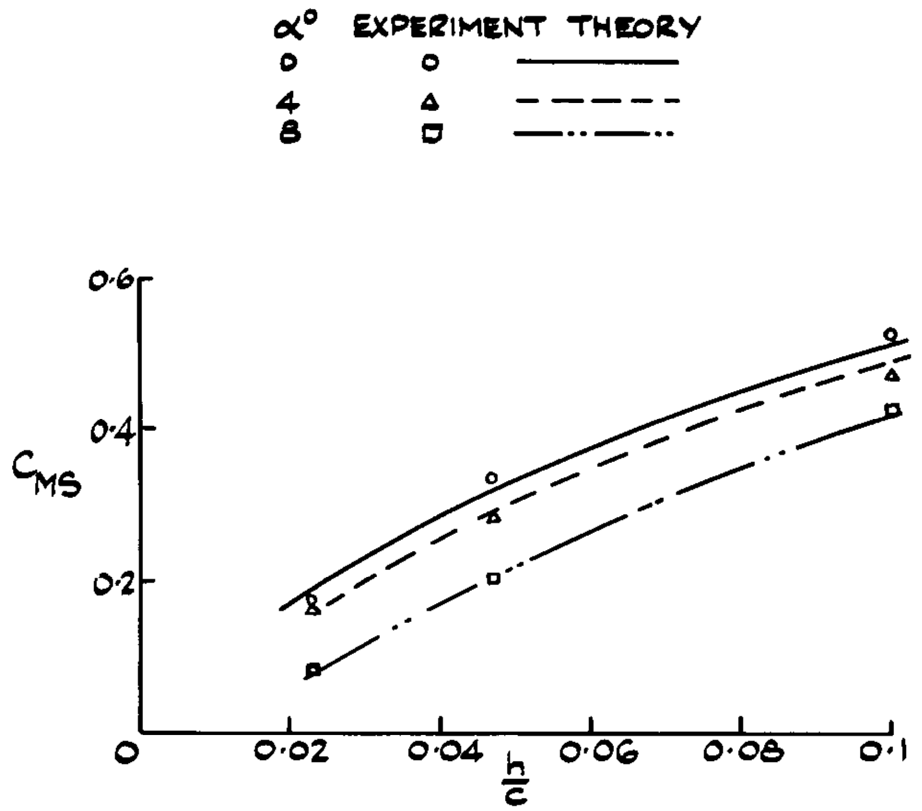


FIG.20. INCREMENTAL PITCHING MOMENT COEFFICIENTS DUE TO TWO-DIMENSIONAL TRAILING EDGE SPOILERS ON AN RAE 102 AEROFOIL

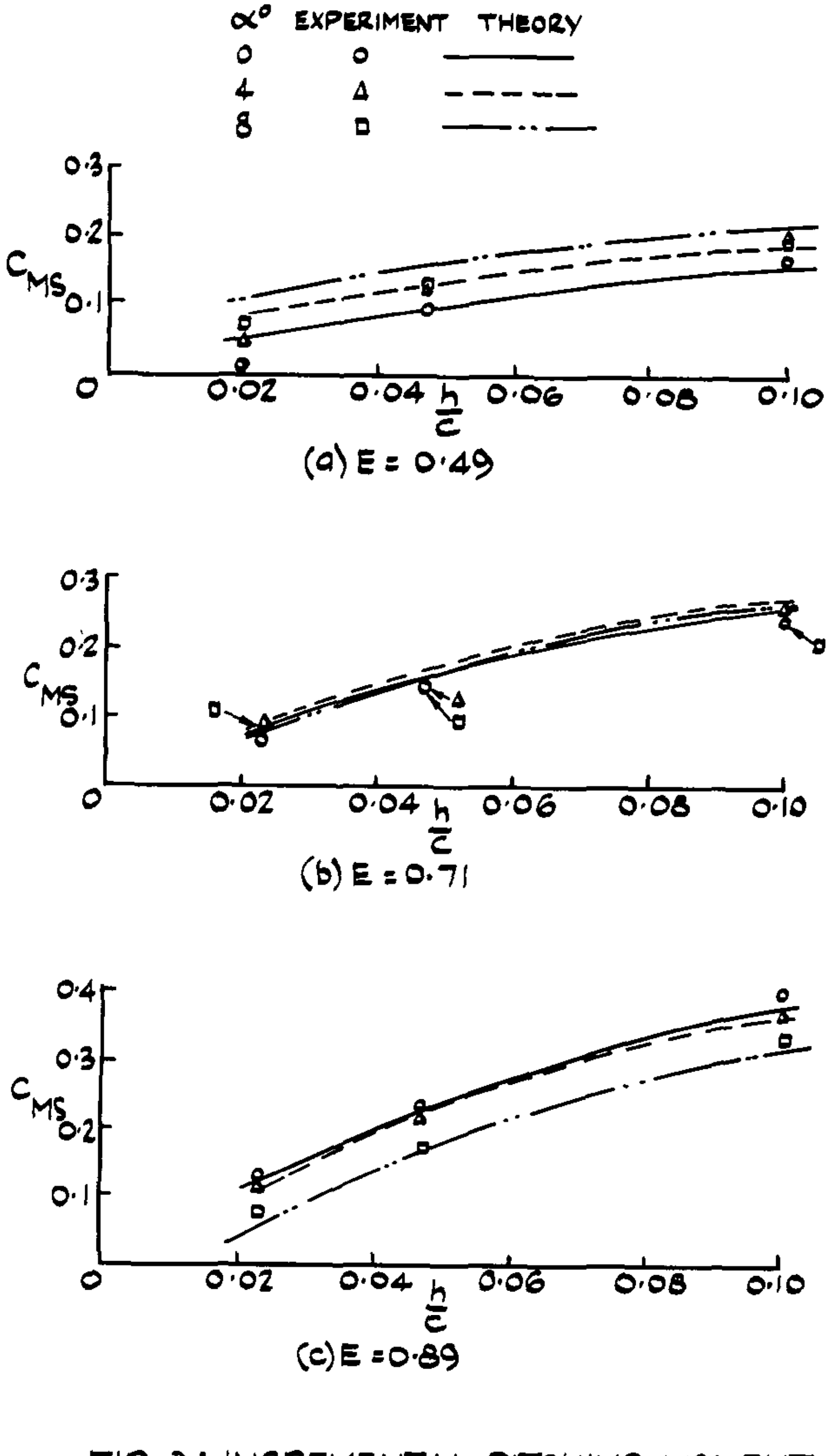


FIG. 21. INCREMENTAL PITCHING MOMENT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS ON AN RAE 102 AEROFOIL

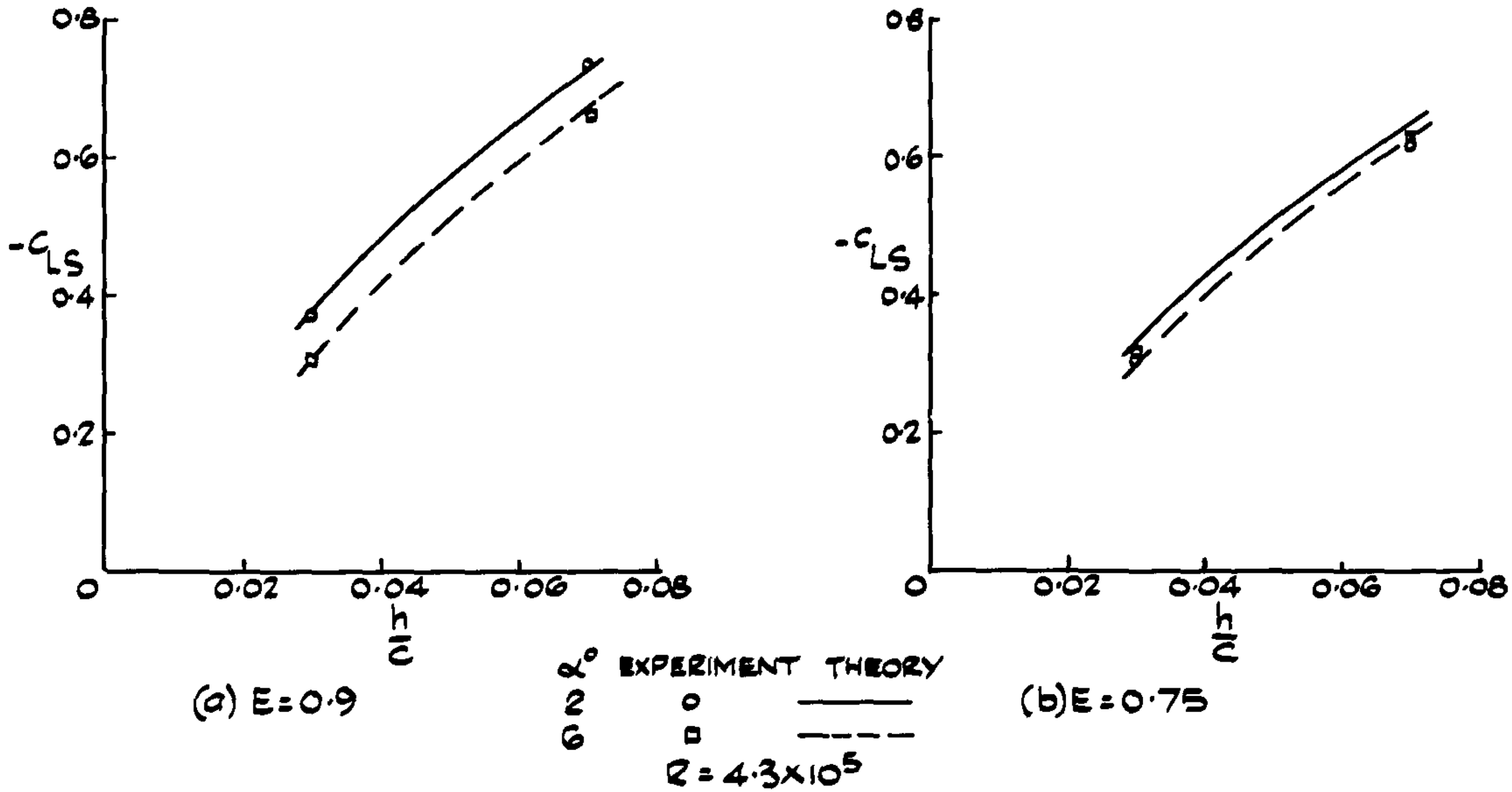


FIG. 22. INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS ON AN RAE 100 AEROFOIL AT $R=4 \cdot 3 \times 10^5$

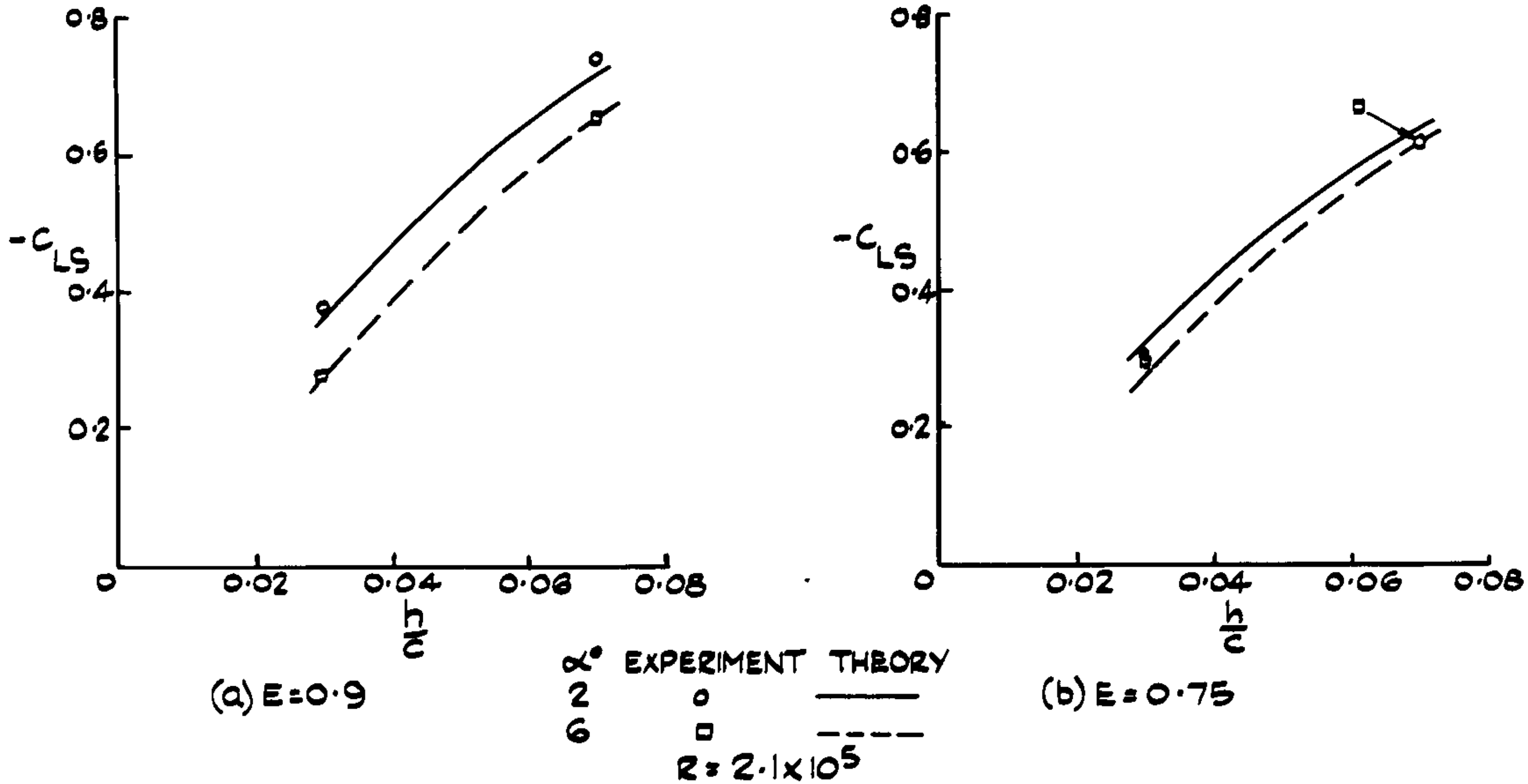


FIG. 23. INCREMENTAL LIFT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS ON AN RAE 100 AEROFOIL AT $R = 2{\cdot}1 \times 10^5$

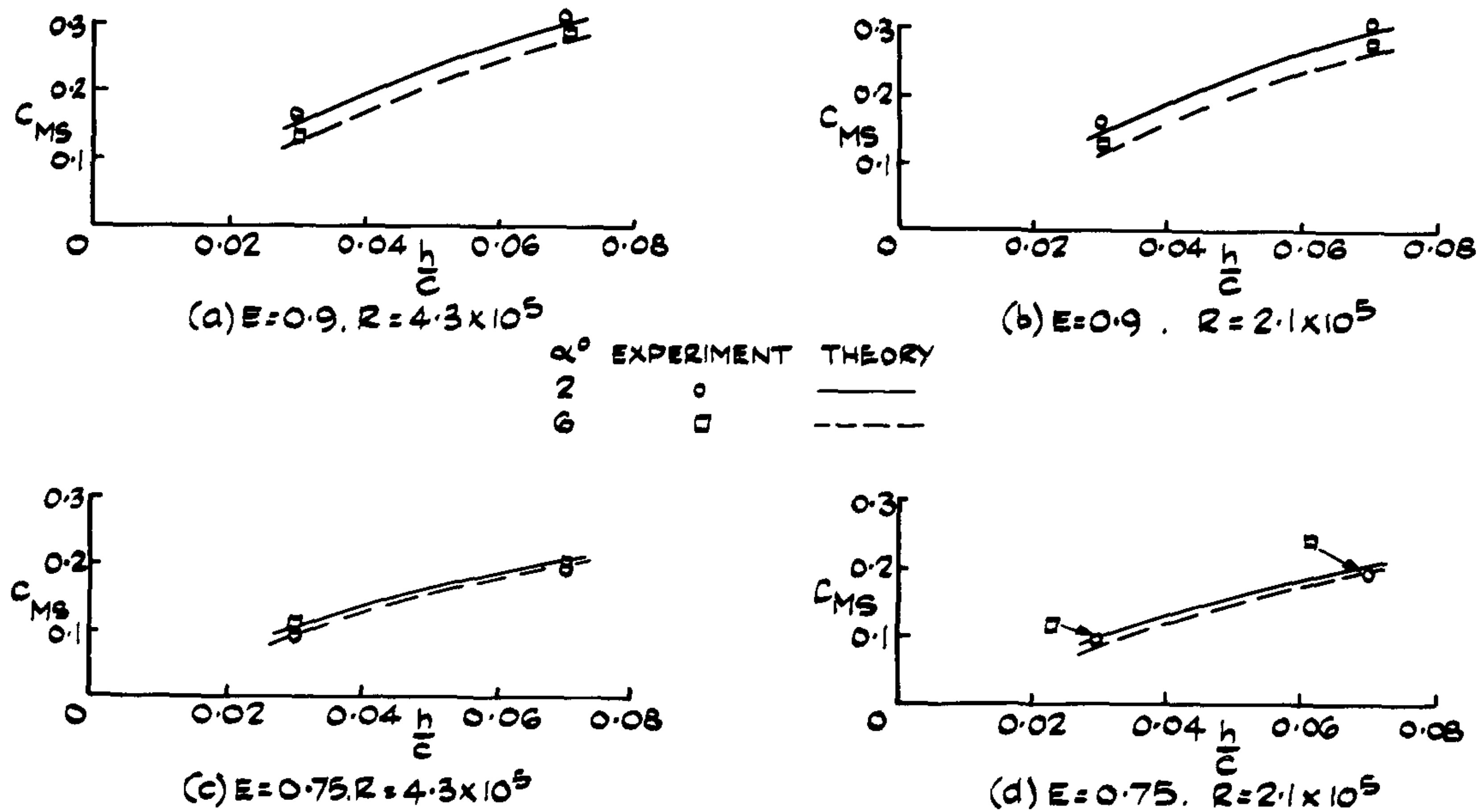


FIG. 24. INCREMENTAL PITCHING MOMENT COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS ON AN RAE 100 AEROFOIL

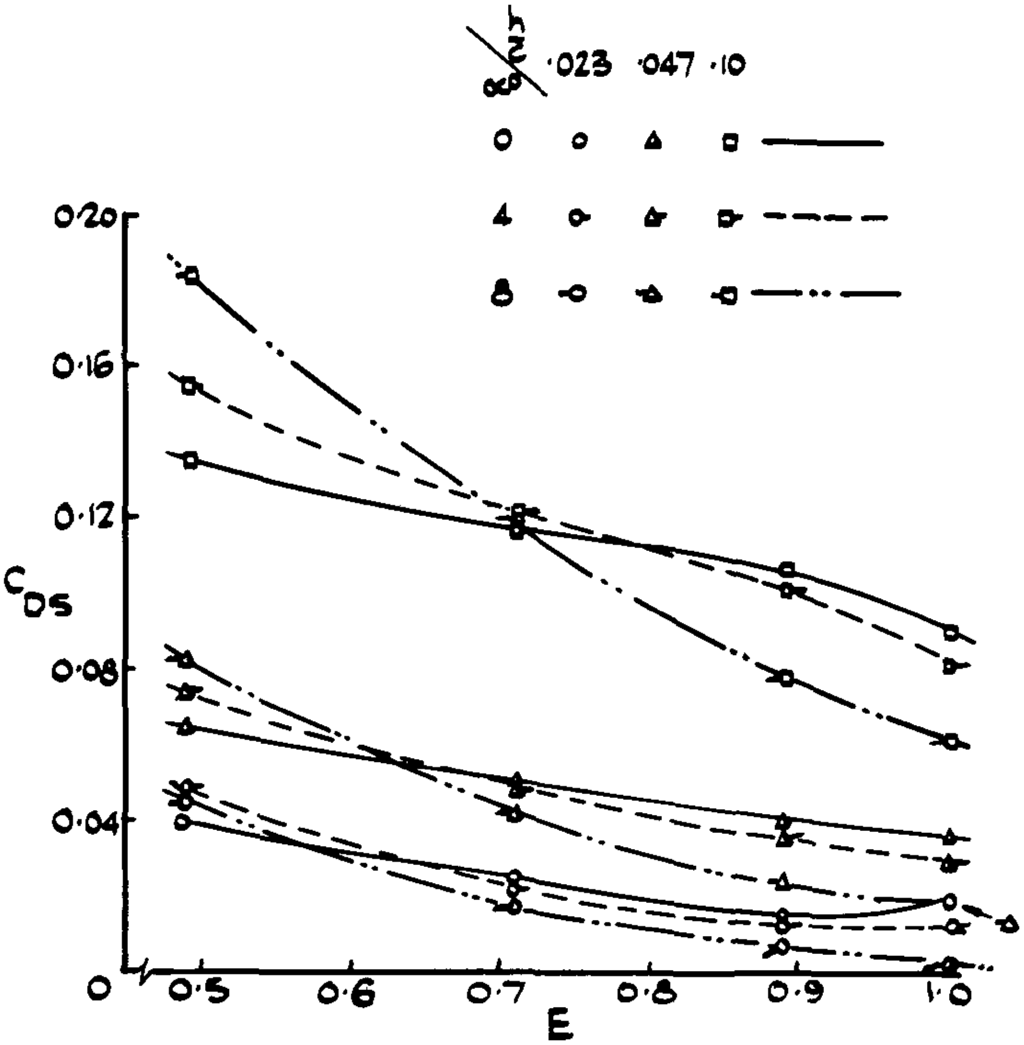


FIG. 25. DEPENDENCE ON α AND E OF THE INCREMENTAL DRAG COEFFICIENTS DUE TO TWO-DIMENSIONAL SPOILERS ON AN RAE 102 AEROFOIL

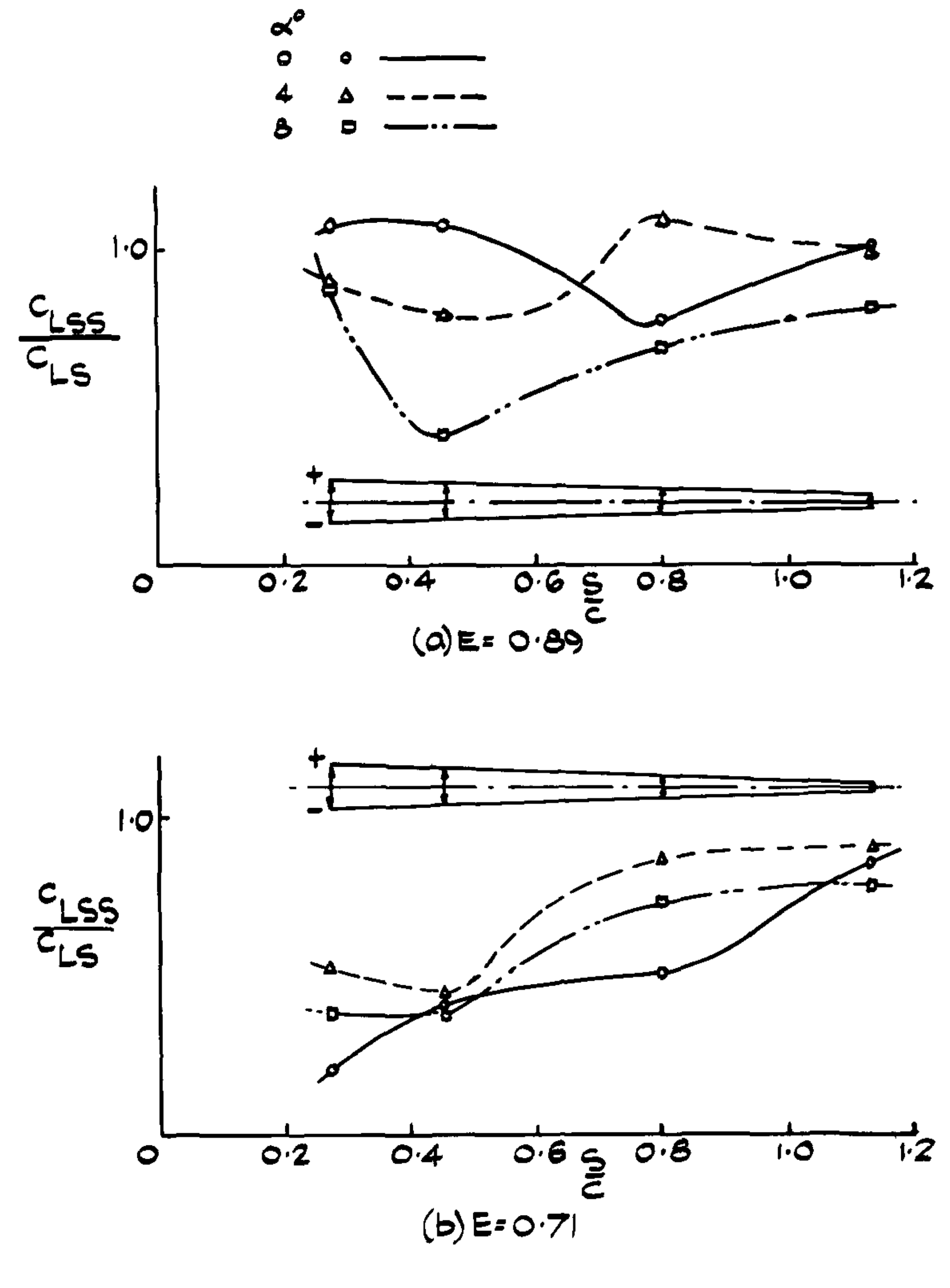
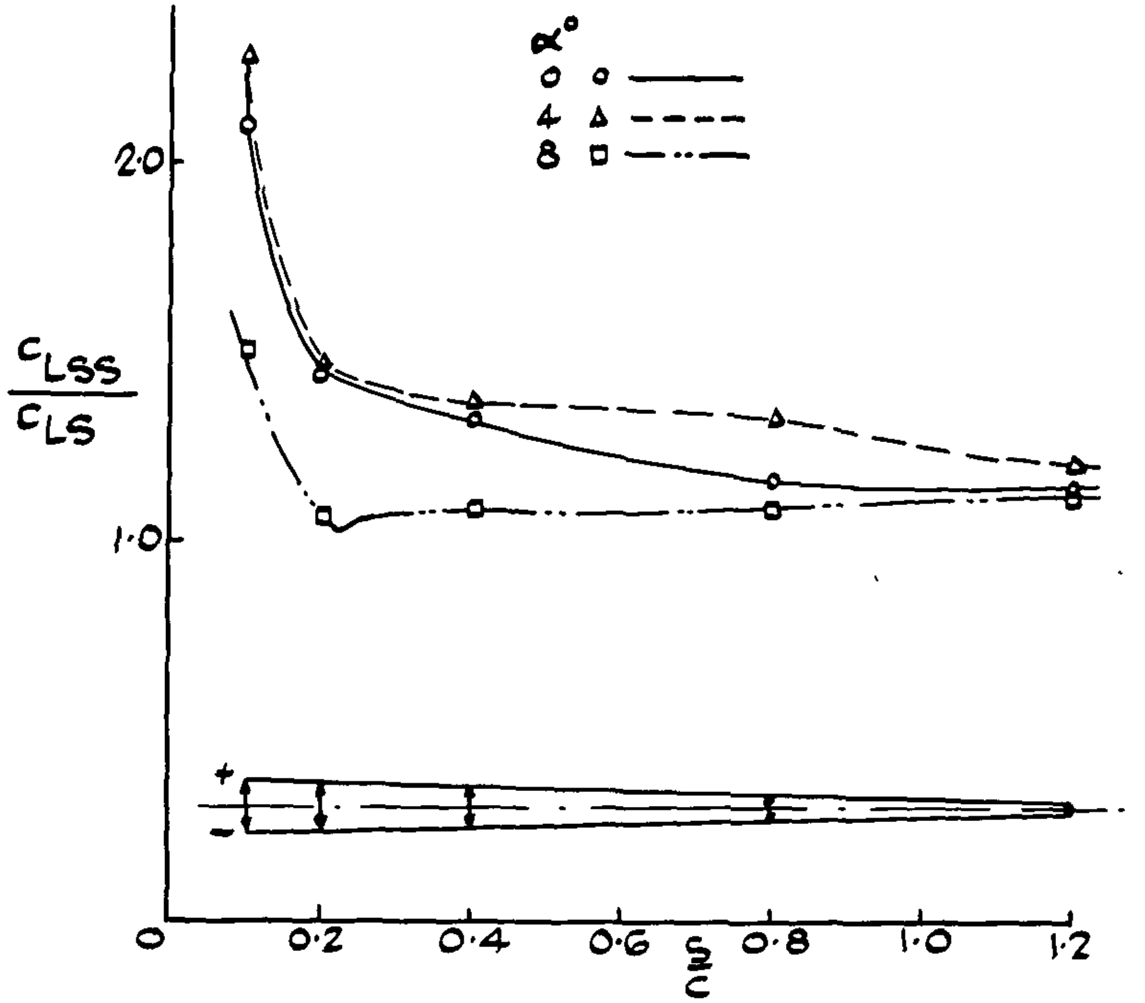
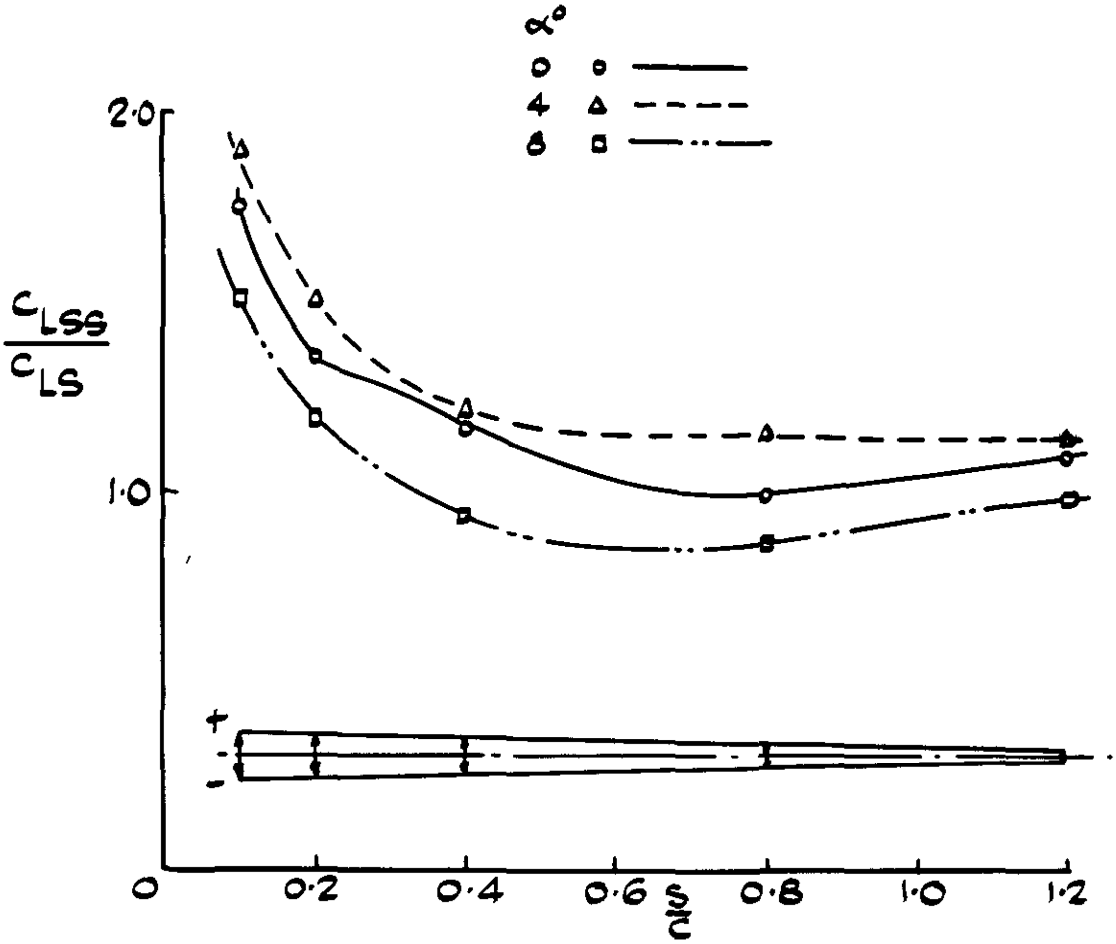


FIG. 26. LIFT EFFECTIVENESS OF FINITE SPOILERS OF $\frac{h}{c}$ = ·023



(b) E = 0·71

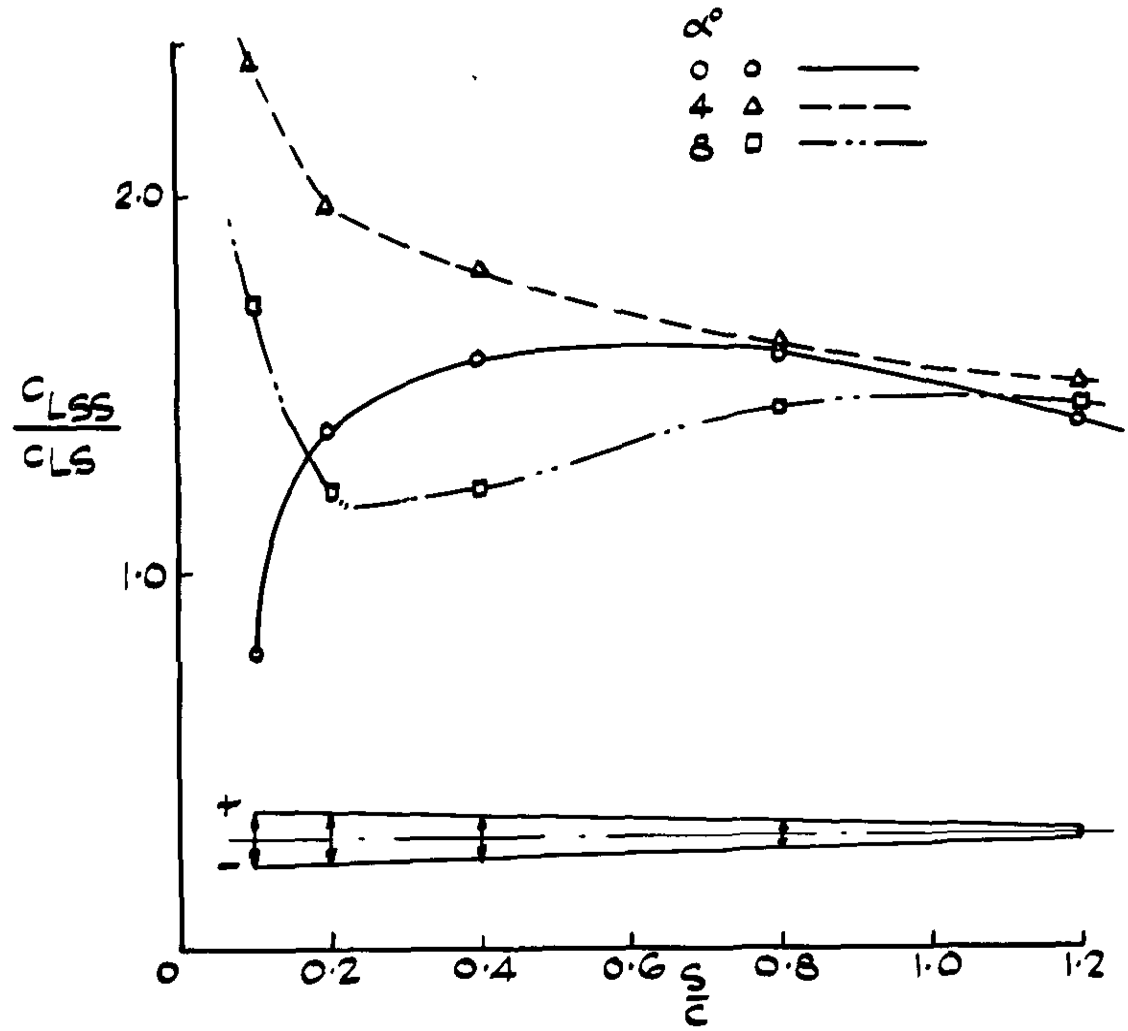
FIG. 27. CONTINUED



(a) E = 0·89

FIG. 27. LIFT EFFECTIVENESS OF FINITE SPOILERS OF $\frac{h}{c} = 0{\cdot}1$

CONTINUED



(c) E = 0·49

FIG. 27. CONCLUDED

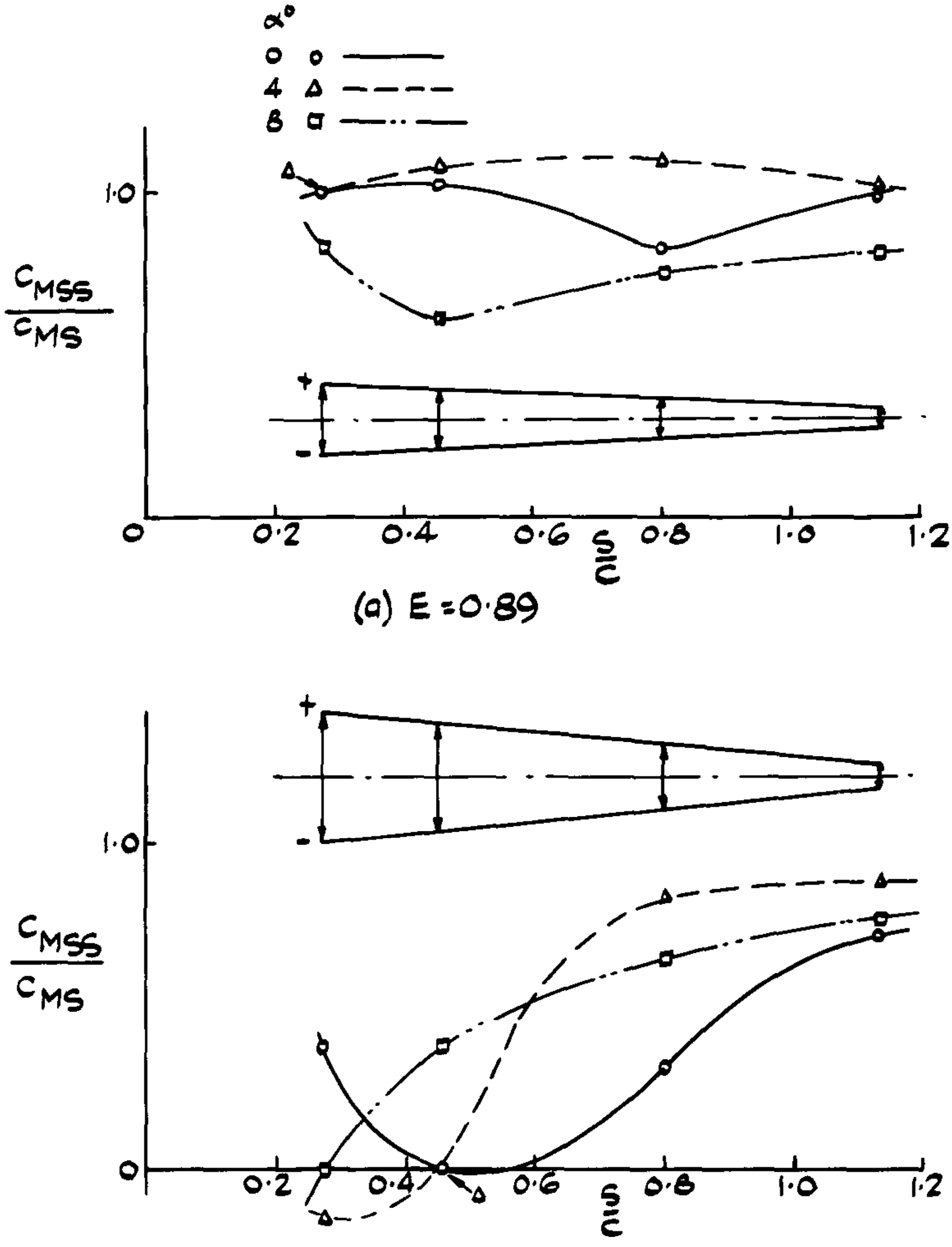
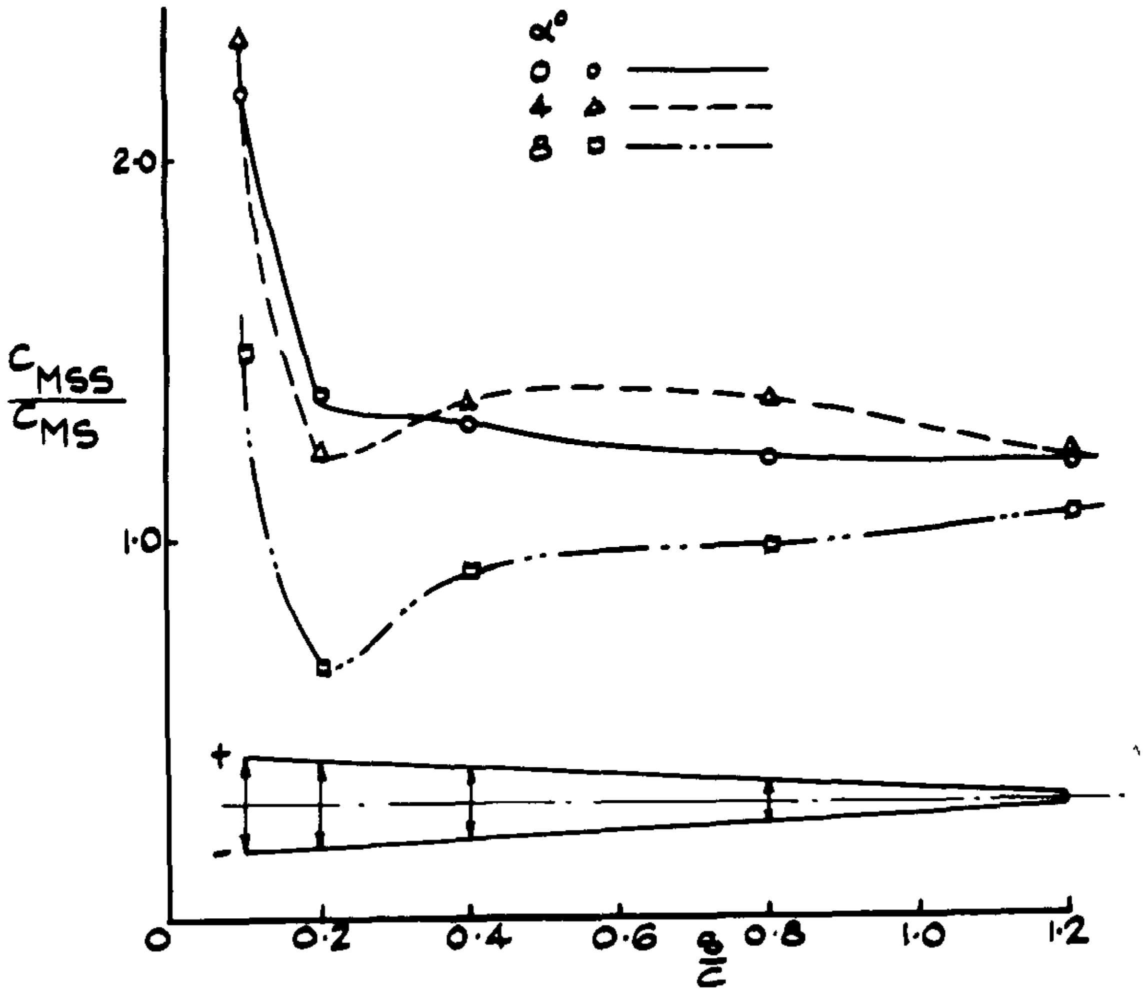
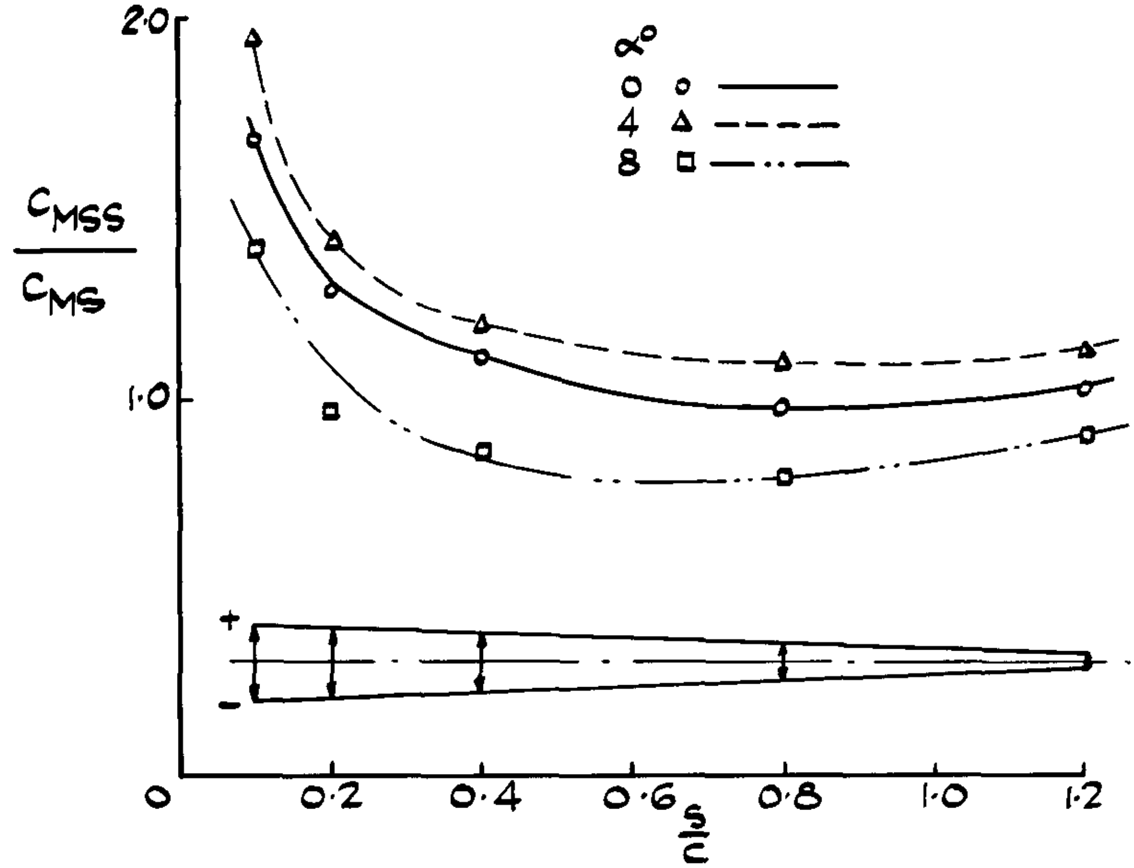


FIG.28. PITCHING MOMENT EFFECTIVENESS OF FINITE SPOILERS OF $\frac{h}{c} = \cdot 023$



(b) E = 0·71

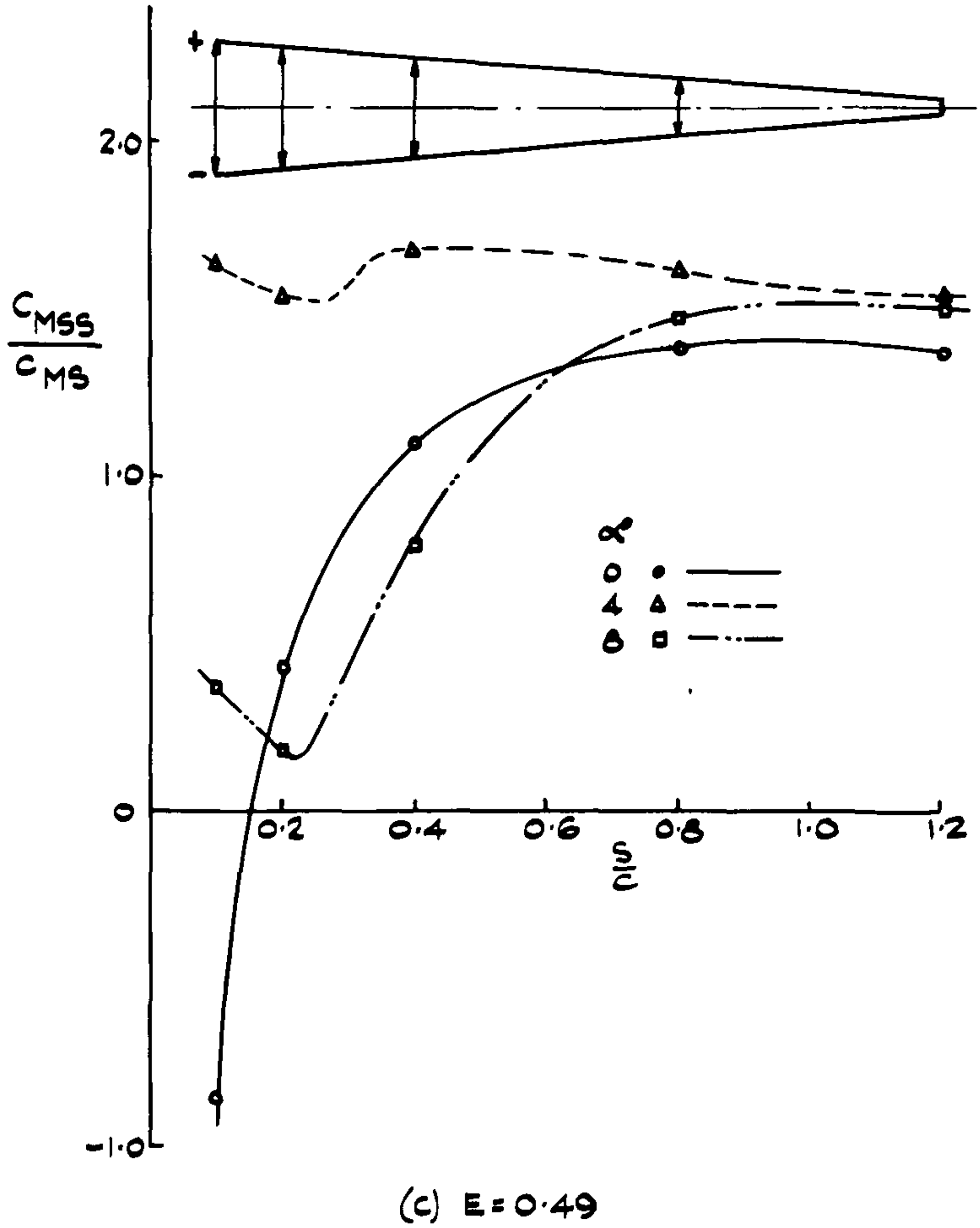
FIG. 29. CONTINUED



(a) E = 0·89

FIG. 29. PITCHING MOMENT EFFECTIVENESS OF FINITE SPOILERS OF $\frac{h}{c} = 0·1$

CONTINUED



(c) E = 0·49

FIG. 29 CONCLUDED

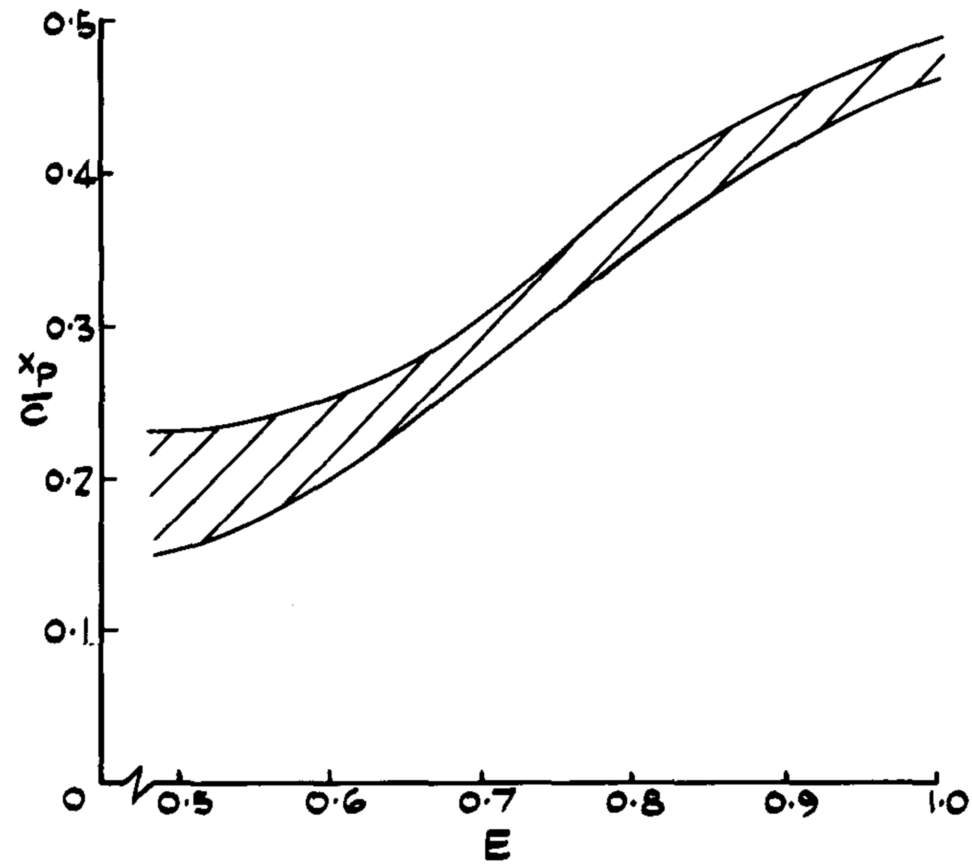


FIG. 30. ENVELOPE OF THE EXPERIMENTAL POSITIONS OF THE INCREMENTAL CENTRE OF PRESSURE DUE TO TWO-DIMENSIONAL SPOILERS ON RAE 100 AND RAE 102 AEROFOILS

A.R.C. C.P. No.887
July, 1965
C. S. Barnes

A DEVELOPED THEORY OF SPOILERS ON AEROFOILS

A theory for the lift and pitching moment coefficients due to two-dimensional normal spoilers on aerofoils in incompressible flow was developed from that of Woods. By making use of experiments on a symmetrical aerofoil fitted with spoilers, the displacement thickness of the boundary layer at the spoiler position and a measure of the pressure in the separated region behind the spoiler were taken into account.

These empirical modifications led to good agreement with experiment over a range of aerofoil incidence. Since a change of incidence is similar in many respects to a change of aerofoil shape it appeared likely that the modified theory would apply over a wide range of aerofoil sections.

Further experiments upon an aerofoil of considerably different shape provided confirmation, good agreement being obtained between theory and experiment.

A.R.C. C.P. No.887
July, 1965
C. S. Barnes

A DEVELOPED THEORY OF SPOILERS ON AEROFOILS

A theory for the lift and pitching moment coefficients due to two-dimensional normal spoilers on aerofoils in incompressible flow was developed from that of Woods. By making use of experiments on a symmetrical aerofoil fitted with spoilers, the displacement thickness of the boundary layer at the spoiler position and a measure of the pressure in the separated region behind the spoiler were taken into account.

These empirical modifications led to good agreement with experiment over a range of aerofoil incidence. Since a change of incidence is similar in many respects to a change of aerofoil shape it appeared likely that the modified theory would apply over a wide range of aerofoil sections.

Further experiments upon an aerofoil of considerably different shape provided confirmation, good agreement being obtained between theory and experiment.

A.R.C. C.P. No.887
July, 1965
C. S. Barnes

A DEVELOPED THEORY OF SPOILERS ON AEROFOILS

A theory for the lift and pitching moment coefficients due to two-dimensional normal spoilers on aerofoils in incompressible flow was developed from that of Woods. By making use of experiments on a symmetrical aerofoil fitted with spoilers, the displacement thickness of the boundary layer at the spoiler position and a measure of the pressure in the separated region behind the spoiler were taken into account.

These empirical modifications led to good agreement with experiment over a range of aerofoil incidence. Since a change of incidence is similar in many respects to a change of aerofoil shape it appeared likely that the modified theory would apply over a wide range of aerofoil sections.

Further experiments upon an aerofoil of considerably different shape provided confirmation, good agreement being obtained between theory experiment.

DETACHABLE ABSTRACT CARDS

A limited series of experiments was made on spoilers of finite span upon the original aerofoil. For spoilers of span greater than 80% of the aerofoil chord it was found that their lift and pitching moment increments could be correlated roughly with those due to two-dimensional spoilers.

A limited series of experiments was made on spoilers of finite span upon the original aerofoil. For spoilers of span greater than 80% of the aerofoil chord it was found that their lift and pitching moment increments could be correlated roughly with those due to two-dimensional spoilers.

A limited series of experiments was made on spoilers of finite span upon the original aerofoil. For spoilers of span greater than 80% of the aerofoil chord it was found that their lift and pitching moment increments could be correlated roughly with those due to two-dimensional spoilers.

C.P. No. 887

Printed and published by
HER MAJESTY'S STATIONERY OFFICE
To be purchased from
49 High Holborn, London W C 1
423 Oxford Street, London W 1
13A Castle Street, Edinburgh 2
109 St Mary Street, Cardiff
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street, Belfast 1
or through any bookseller

Printed in England

C.P. No. 887

S O Code No 23-9016-87