THE AERODYNAMICS OF JET FLAPS

By JOHN WILLIAMS*, S. F. J. BUTLER** and M. N. WOOD**

Summary—With jet-flap wings, a considerable proportion of the jet efflux leaves the wing trailing-edge as a plane sheet inclined to the relative mainstream. The lift generated is several times the corresponding vertical component of the jet momentum, while the sectional thrust lies between the corresponding horizontal component and full jet momentum.

This paper, after introducing briefly the origin and basic concepts, examines the considerable progress made on jet-flap aerodynamics during the past five years. The aspects discussed comprise lift, pitching moments and downwash, thrust, sideslip derivatives, and the effects of ground proximity. Some associated implications with regard to jet-flap aircraft performance, stability and control are also mentioned.

1. INTRODUCTION

DURING the past half-century of aircraft development, it has been increasingly necessary to devise more poweful methods for improving the lifting efficiency and stability characteristics of aircraft wings at low speeds, with the minimum penalty on the aircraft cruising performance. Such developments have become essential to ensure moderate take-off and landing performance of heavily loaded and high-speed aircraft, to meet the renewed demand for extremely short and slow take-off and landing. and to improve the transition behaviour of new types of vertical take-off aircraft. The method of boundary-layer control (B.L.C.), by now well established, employs a small proportion of the installed engine power or airflow (say 10%) to induce blowing or suction at the wing and flap surface, for the prevention of flow separation; thereby, the ideal lifting efficiency of the system corresponding to potential flow can be sensibly realized. In contrast, the conventional round jets from gas-turbine engines can be tilted towards the vertical to produce a direct jet lift roughly equal to the corresponding vertical component of the rate of ejection of momentum.

* Superintendent of Low-Speed Tunnels Division, Aerodynamics Department, Royal Aircraft Establishment.

** Senior Scientific Officer, Low-Speed Tunnels Division, Aerodynamics Department, Royal Aircraft Establishment.

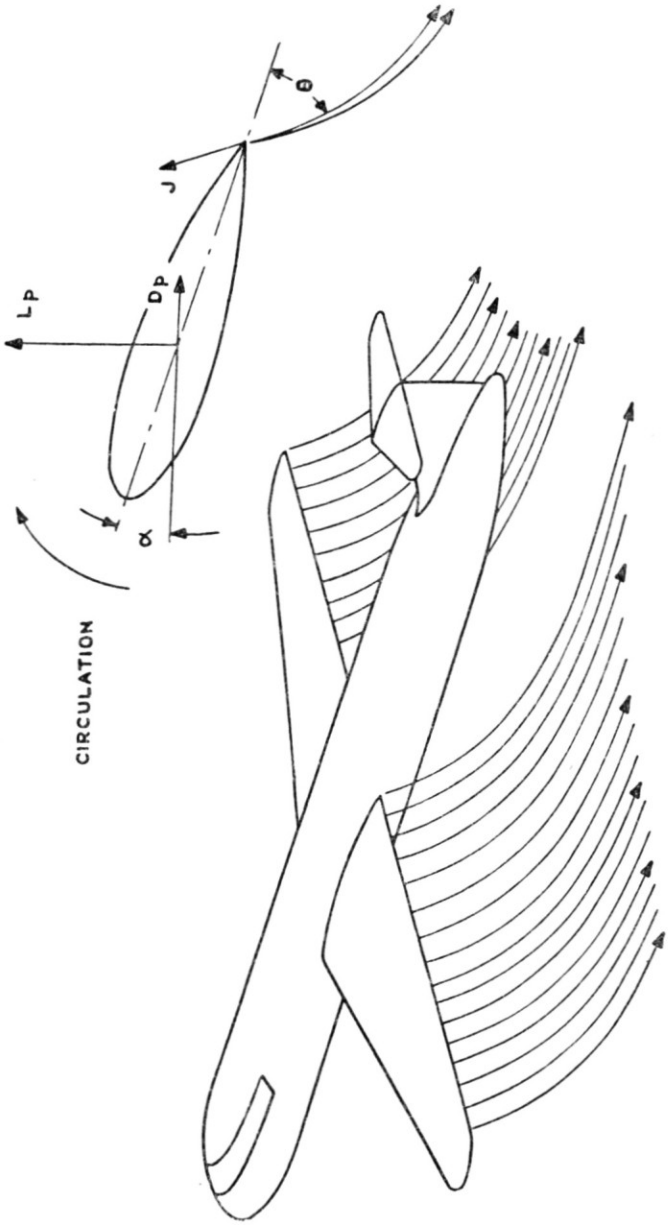

FIG. 1. Jet-flap aircraft.

From one aspect, the jet-flap scheme is a natural extension of slot blowing over trailing-edge flaps for B.L.C., using much higher quantities with a view to increasing the effective chord of the flap to produce so-called "super-circulation" about the wing. Examples of this were available more than 20 years ago, from the experiments of Lyon in Britain, Bamber in the U.S.A., Hagedorn in Germany and Valensi in France. However, the concept proper originated much more recently, from a search for methods of using the efflux of turbo-jet engines not merely to provide propulsion and direct jet lift by tilting, but also to generate significant favourable lift on the wing with the minimum reduction of propulsive thrust. Ideally, the lifting and propulsive systems of turbo-jet aircraft might then be completely integrated with advantage (Fig. 1).

The term jet flap implies that the gas efflux is directed to leave the wing trailing-edge as a plane jet at an angle to the mainstream, so that an asymmetrical flow pattern and circulation is generated about the aerofoil in a manner somewhat analogous to a large trailing-edge flap. By this means, the lift from the vertical component of the jet momentum is magnified several times by "pressure-lift" generated on the wing surface, while the sectional thrust (see section 4) lies between the corresponding horizontal component and the full jet momentum. To facilitate variation of jet-angle to the mainstream direction, the air is usually ejected from a slot forward of the trailing-edge, over a small flap whose angle can be simply varied (Fig. 2).

In Britain, jet-flap studies originated at the N.G.T.E.[1] towards the end of 1952. The pioneer investigations throughout 1953 included first studies of the basic concepts and their practical application by Davidson and Stratford, two-dimensional pressure-plotting experiments on simple small-scale models by Dimmock at N.G.T.E., together with complementary three-dimensional experiments by Williams and Alexander at N.P.L. to explore quickly the nature and importance of finite aspect-ratio effects. About the same time, the first rigorous theory for the two-dimensional jet-flap aerofoil in inviscid flow was also formulated. Since then[2], the basic aerodynamic principles for both two-dimensional and three-dimensional jet-flap wings have been well established by a joint R.A.E. and N.P.L. programme of both experimental and theoretical research. This has included studies of basic stability and control, as well as of lift and thrust aspects.

Similar research investigations have been carried out elsewhere, particularly in France and the United States. In this short paper, further reference to such work and to some interesting developments has had to be omitted. Even so, special attention must be drawn to the electrolytic tank techniques devised by Malavard at O.N.E.R.A.[3] for the numerical

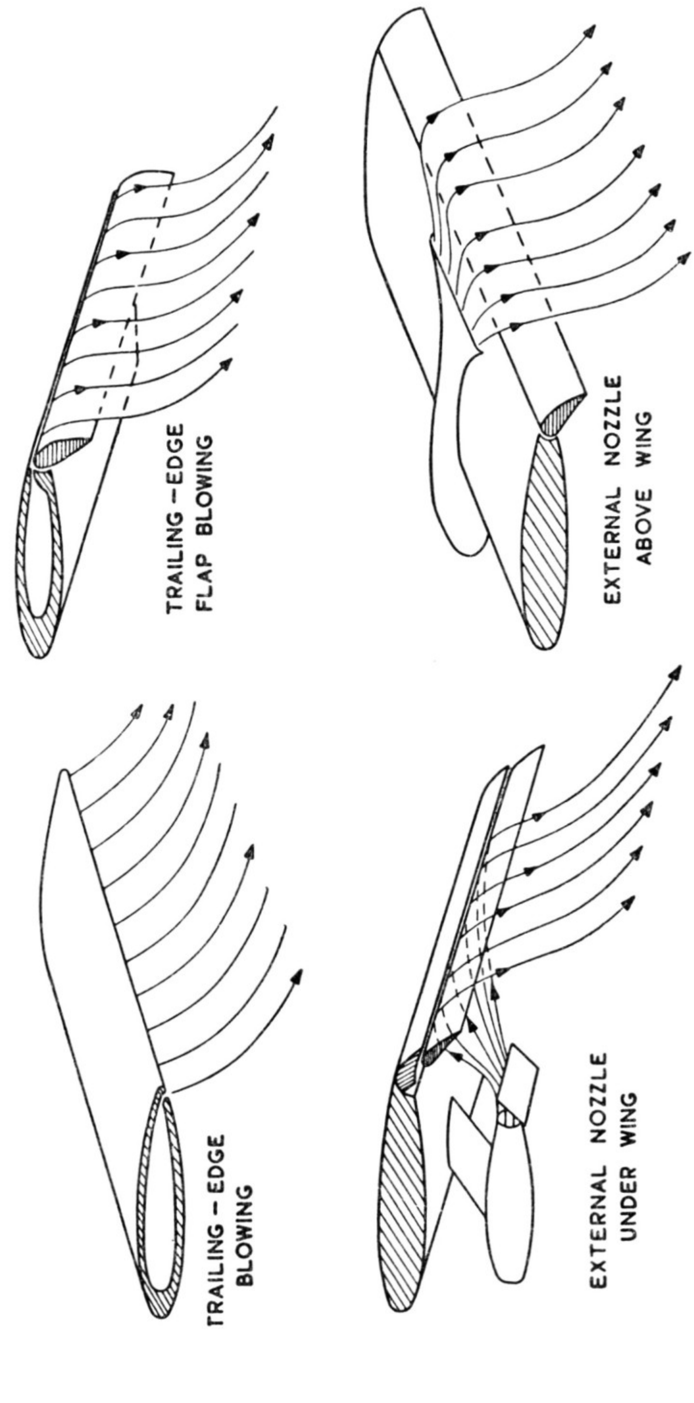

FIG. 2. Some Jet-lfap schemes.

treatment of jet-flap wing theory, the N.A.S.A. external-flow jet-flap arrangements[5] (Fig. 2), the application of jet flaps to helicopter rotors by Dorand[4] and others, and jet-flap "spoilers" as a method of roll control.

This paper, after introducing briefly some basic concept (section 2) examines the considerable progress made on jet-flap aerodynamics during the past five years and draws attention to some major problems which need further study. For convenience and brevity, most of the illustrations are taken from R.A.E. and N.P.L. research work. The aspects discussed comprise lift (section 3.1), stalling behaviour (section 3.2), pitching moments and downwash (section 3.3), thrust (section 4), sideslip derivatives (section 5), and the effects of ground proximity (section 6). Some associated implications with regard to jet-flap performance, stability and control are also mentioned.

2. SIMPLE CONCEPTS AND BASIS OF ANALYSIS

The mainstream flow past an aerofoil with the jet emerging from the trailing-edge at an angle to the mainstream direction tends to turn the jet streamwise causing a pressure difference across it. Likewise, the jet interferes with the mainstream flow over the aerofoil surface, so generating pressure force on it (Fig. 3). The jet momentum coefficient $C_\mu(\equiv M_J V_J/q_0 S)$, rather than the jet quantity coefficient $C_Q(\equiv M_J/\varrho_0 V_0 S)$ or the ratio V_J/V_0 of jet speed to mainstream speed, is well established as the major non-dimensional parameter for the correlation of results, together with the jet angle Θ and wing incidence α.

The "total" lift C_L on the jet-flap aerofoil represent a considerable magnification of the direct jet-reaction lift $C_\mu \sin\overline{\theta+\alpha}$ from the corresponding vertical component of the jet momentum, because of the additional pressure lift on the aerofoil (Fig. 6*a*). The centre of lift, located at about half-chord for low C_μ-values, moves further rearwards with increasing C_μ at fixed α and θ, and the aerodynamic centre tends to move aft of the quarterchord position. The sectional thrust coefficient C_T (see section 4) on the aerofoil exceeds the jet-reaction contributions $C_\mu \cos\overline{\theta+\alpha}$ but, as $\overline{\theta+\alpha}$ is increased, falls well below the ideal theoretical value C_μ for two-dimensional inviscid flow. To turn the jet through the required angles in practical applications, the air would probably be ejected over a small T.E. flap whose angle could be simply varied, rather than by inclining the direction of the blowing slit to the chord-line. The minimum flap size acceptable in practice is mainly determined by the need for a large enough ratio of flap knee radius to slot width (say at least 5 to 1), in order to ensure that the jet clings to the flap upper surface. Blowing over such a trailing-edge flap, rather than from the wing trailing-edge, also raises the lift considerably but introduces a drag penalty due to skin friction over the flap. As regards finite aspect-ratio effects, the spanwise distribution of pressure-lift loading induced by blowing is not far different from that for a conventional wing at incidence

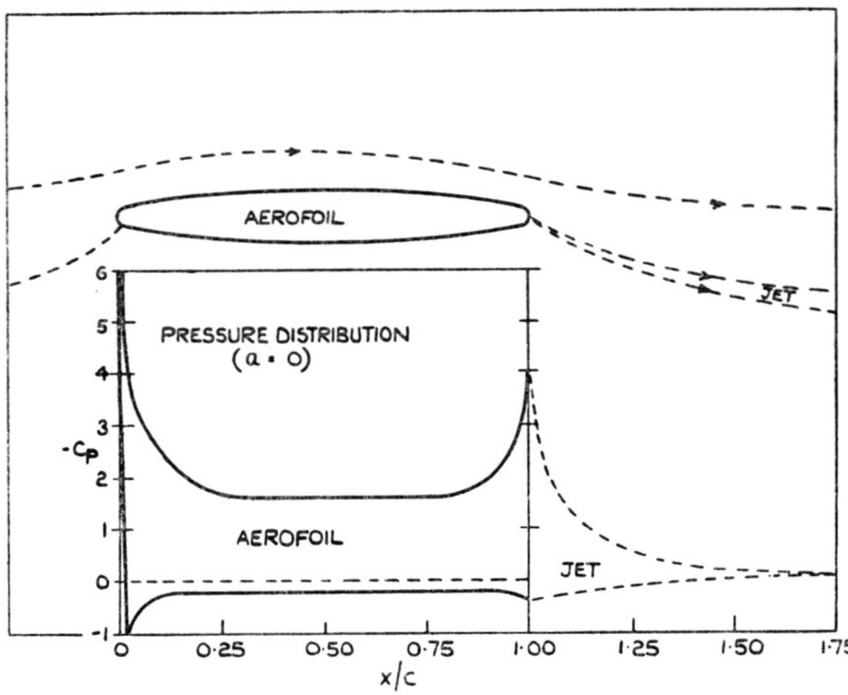

FIG. 3. Basic principle of jet-flap aerofoil.

and, at small C_μ-values, conventional aspect-ratio corrections for pressure-lift and pressure-drag could be used as a rough working rule. However, in the following sections, these and other points are discussed more rigorously and comprehensively in the light of the available theoretical treatments and wind-tunnel results, particularly those of R.A.E. and N.P.L.

The basic theoretical properties of a thin two-dimensional jet in inviscid flow were formulated by Maskell and Gates, together with the overall momentum relations satisfied by the two-dimensional jet-flap aerofoil. Subsequently, jet-flap theories were developed for the case of the thin wing and jet in inviscid incompressible flow, excluding mixing between the mainstream and the jet. The two-dimensional problem was solved by Spence using a treatment akin to classical "mean-line" theory, both for ejection from the trailing-edge and over a plain (hinged) flap. This treatment was extended to the case of a finite aspect-ratio wing with a full-span jet flap by Maskell, following the classical Prandtl lifting-line theory, the equations being made tractable by prescribing an elliptic spanwise distribution of both wing chord and jet-momentum with constant jet-angle over the span. Such treatments have also been further developed for the estimation of the associated wing pressure distributions, downwash and jet path, as well as of damping in roll and longitudinal stability derivatives on a quasi-steady basis.

The experimental results on which the subsequent analysis is based were mostly derived from force measurements, flow studies and some surface pressure plotting, by Williams and Alexander on an N.P.L. rectangular wing half-model in the N.P.L. 13 ft × 9 ft tunnel, by Wood on the same model in the R.A.E. No. 2 $11\frac{1}{2}$ ft × $8\frac{1}{2}$ ft tunnel, and by Butler on an R.A.E. complete model in the R.A.E. tunnel. The half-model (Fig. 4) was of aspect-ratio 6 with a 12% thick wing section, being intended for basic research on lift, pitching moments, thrust and downwash to follow up the exploratory tests on small-scale pressure-plotting models. The extent of the trailing-edge flap and the wing nose shape were varied, primarily to investigate the effect on thrust and on flow separation respectively. The complete model (Fig. 5) was intended to provide basic information on both longitudinal and lateral stability derivatives, and used a highly cambered thick wing section (NACA 4424) to minimise flow separation at high lift coefficients. The influence of wing geometry was studied by increasing separately the aspect-ratio from 6 to 9, the dihedral by 5° and the sweepback by 10°. The effect of ground proximity was investigated on the unswept aspect-ratio 9 version with +4° dihedral, at three ground clearances ($H/c = 1{\cdot}5$, $2{\cdot}25$ and $3{\cdot}25$). This model is now being modified for oscillatory derivative measurements.

For the evaluation of the jet momentum coefficient C_μ, the jet speed V_J is usually determined theoretically, by assuming isentropic expansion from the total pressure (and temperature) in the slot throat to the mainstream static pressure. The mass-flow rate M_J can likewise be estimated theoretically for an assigned slot throat area, but in experimental work it is best measured, so that errors due to throat area determination and neglecting viscous effects are avoided. Alternatively, the value of the jet momentum can be specified as the measured installed static reaction, J, for the appropriate T.E. flap deflection. But corrections should then be applied for the measured pressure-drag arising from local mainstream flows induced by the jet efflux, jet-drag forces on slot spacers and the like, and differences in the mass-flow rate for static and mainstream-on conditions at a prescribed duct pressure. As regards the choice of wing reference area S, there is of course some freedom for cases of part-span blowing or where there is a fuselage cut-out. It is then necessary to make the distinction between an overall momentum coefficient C_μ based on

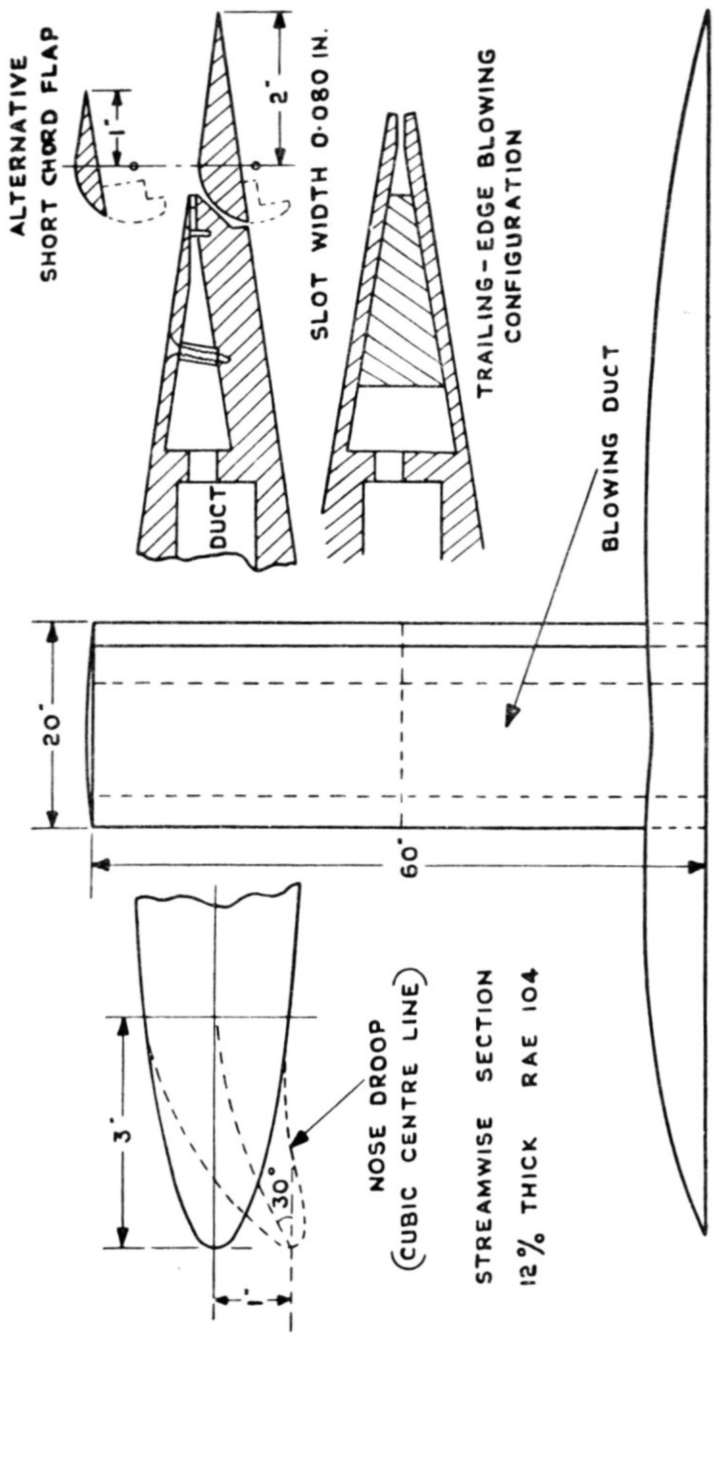

FIG. 4. Half-model of jet-flap rectangular wing.

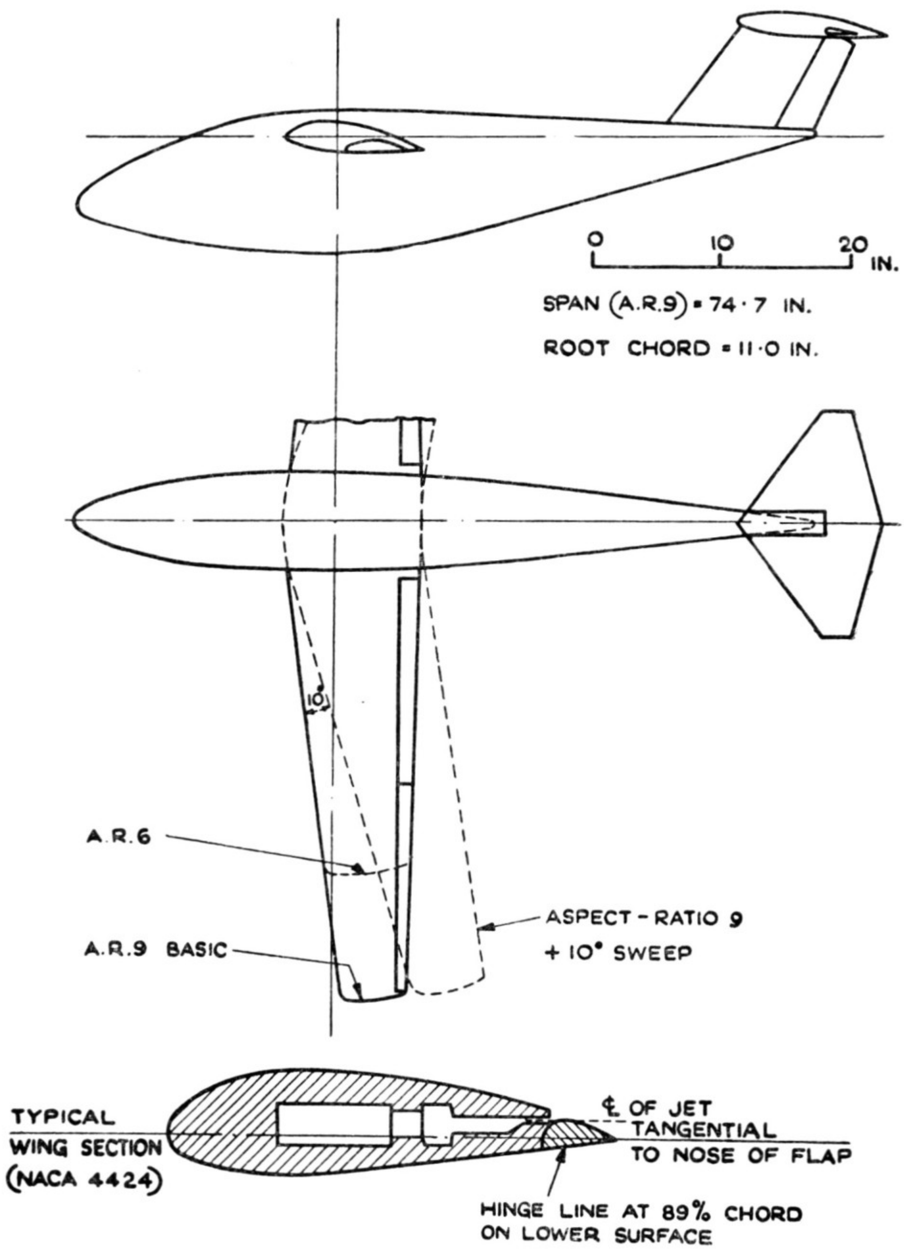

FIG. 5. Jet-flap complete model.

the gross wing area S used for defining overall force coefficients, and a sectional momentum coefficient C'_μ based on the wing area S' corresponding to the spanwise extent of the blowing slot. The significance and importance of the foregoing remarks are brought out further in the subsequent analysis on lift and thrust aspects.

In most model experiments, the air is fed into the model from an outside source, and not extracted from the oncoming mainstream as in most flight applications. Hence, in using the results of the following analysis for project work, some allowances may be needed. For example, by simple momentum considerations, the model thrust coefficient with such an external supply is higher by 2 C_Q than if the air were taken in from the mainstream and pressurised without losses. The effects on the other forces and moments must also be borne in mind if the intake momentum is large.

3. LIFT ASPECTS

The lift behaviour of jet-flap wings has already been referred to qualitatively in section 2, being illustrated by the experimental results shown in Fig. 6. In the present section the various aspects will be discussed more fully, particularly with regard to practical estimation, including lift increments and corresponding increases in lift-incidence curve slopes, stalling behaviour, pitching moments and associated trimming problems, and downwash effects at the tail.

3.1 *Lift Increments*

The formulae of linearised inviscid flow theory offer a convenient starting point for a discussion of results. The lift $(C_L)_\infty$ for a two-dimensional thin flat plate at incidence α, with blowing over a hinged flap to provide a jet deflection Θ, is given by

$$(C_L)_\infty = \theta\left(\frac{\partial C}{\partial \theta}\right)_\infty + \alpha\left(\frac{\partial C_L}{\partial \alpha}\right)_\infty \tag{1}$$

The sectional derivative $(\partial C_L/\partial \theta)_\infty$ is purely a function of the sectional momentum coefficient C'_μ and flap-chord ratio c_f/c, while $(\partial C_L/\partial \alpha)_\infty$ is synonymous with $(\partial C_L/\partial \theta)_\infty$ at $c_f/c = 1$. The following simple interpolation formulae fit the computed values for $c_f/c = 0$ (T.E. blowing) at C'_μ values of 1 and 4 and asymptotically as $C'_\mu \to 0$.

$$\left.\begin{aligned}\left(\frac{\partial C_L}{\partial \theta}\right)_\infty &= [4\pi C'_\mu(1+0{\cdot}151 C'^{1/2}_\mu+0{\cdot}139 C'_\mu)]^{1/2}\\ \left(\frac{\partial C_L}{\partial \alpha}\right)_\infty &= 2\pi(1+0{\cdot}151\, C'^{1/2}_\mu+0{\cdot}219 C'_\mu)\end{aligned}\right\} \tag{2}$$

Fig. 7 shows the variation of $(\partial C_L/\partial \theta)_\infty$ with both C'_μ and c_f/c.

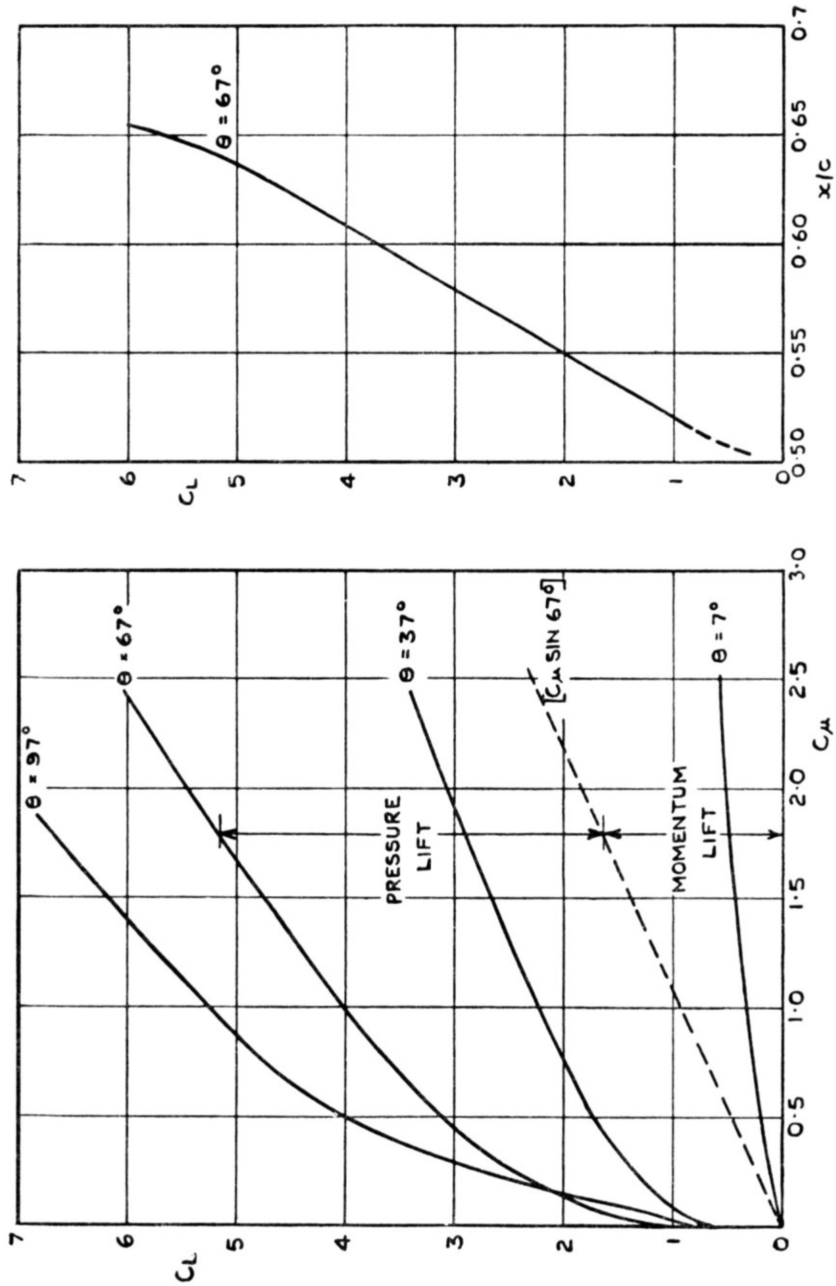

FIG. 6a Variation of lift and centre of lift at zero incidence (aspect-ratio 6 half-model)

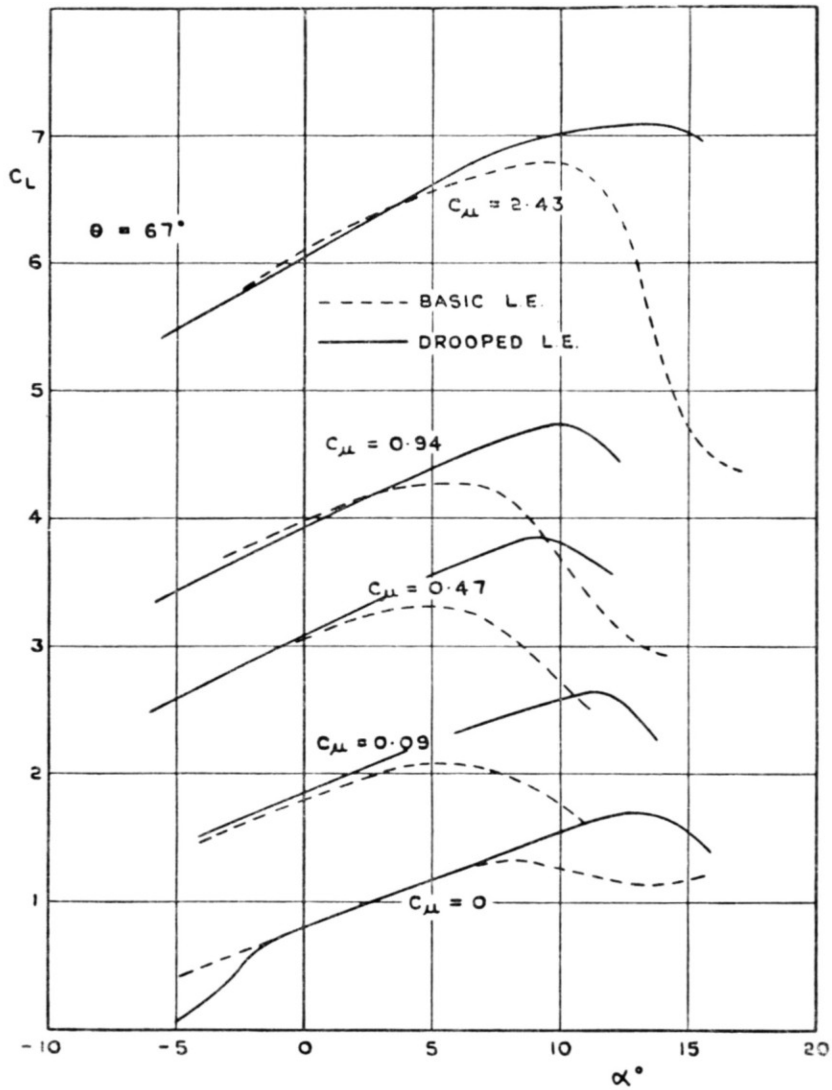

FIG. 6*b*. Effect of C_μ and nose droop on lift-incidence curves (aspect-ratio 6 half-model).

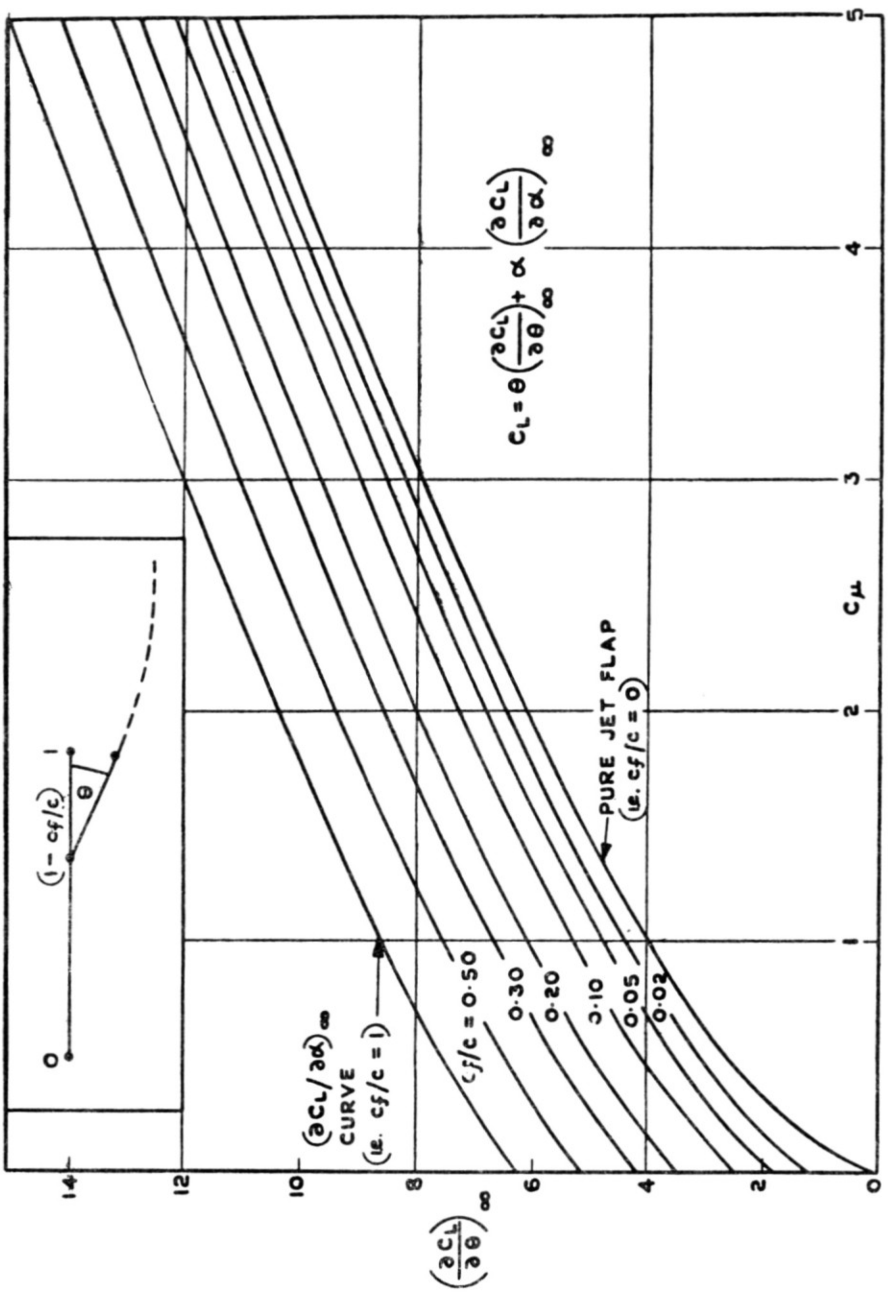

FIG. 7. $\left(\frac{\delta C_L}{\delta \theta}\right)_\infty$ for thin aerofoil with T.E. flap blowing.

The lift on a wing of aspect-ratio A with a full-span jet flap can again be expressed by a relation of the type (1). The derivatives $(\partial C_L/\partial\theta)$ and $(\partial C_L/\partial\alpha)$ for the finite aspect-ratio wing are obtained by multiplying the corresponding two-dimensional values $(\partial C_L/\partial\theta)_\infty$ and $(\partial C_L/\partial\alpha)_\infty$ by the factor

$$\left.\begin{aligned} F(A, C_\mu') &= \frac{A+\left(\dfrac{2C_\mu'}{\pi}\right)}{A+\left(\dfrac{2}{\pi}\right)\left(\dfrac{\partial C_L}{\partial\alpha}\right)_\infty-2(1+\sigma)} \\ &\simeq \frac{A+\left(\dfrac{2C_\mu'}{\pi}\right)}{A+2+0{\cdot}604C_\mu'^{1/2}+0{\cdot}876C_\mu'} \end{aligned}\right\} \tag{3}$$

at small C_μ' or large A*.

On the basis of semi-empirical arguments, the lift on a jet-flap wing may be written more generally as

$$C_L = F\left[\left(1+\frac{t}{c}\right)\left\{\lambda\theta\left(\frac{\partial C_L}{\partial\theta}\right)_\infty+\nu\alpha\left(\frac{\partial C_L}{\partial\alpha}\right)_\infty\right\}\right]-\frac{t}{c}C_\mu(\theta+\alpha) \tag{4}$$

The effect of thickness-chord ratio is taken into account by increasing the sectional pressure-lift in the proportion $(1+t/c)$, roughly corresponding to the ratio of the sectional lift-incidence curve slope without blowing to the value 2π for a thin flat-plate. Allowance for part-span flaps and fuselage cut-out is included by introducing spanwise extant factors λ and ν to correct the lift increments due to jet deflection Θ and wing incidence α respectively. Simple considerations give

$$\lambda \simeq \frac{S'}{S}, \qquad \nu \simeq \frac{S'\left(\dfrac{\partial C_L}{\partial\alpha}\right)_\infty+(S-S')\left(\dfrac{\partial C_L}{\partial\alpha}\right)_{\infty,\,C_\mu=0}}{S\left(\dfrac{\partial C_L}{\partial\alpha}\right)_\infty}$$

where the sectional derivatives are evaluated using the mean sectional momentum coefficient $C_\mu' = C_\mu S/S'$. In fact, when the flaps are virtually full-span except for the fuselage cut-out, experimental results for the complete model indicate that ν can be more simply taken as unity with the derivative $(\partial C_L/\partial\alpha)_\infty$ evaluated for the overall C_μ-value, instead of the sectional coefficient C_μ'.

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* More specifically,

$$\sigma = \frac{(1-\lambda)\left(\dfrac{C_\mu'}{\pi A}\right)}{\lambda-(1-\lambda)\left(\dfrac{C_\mu'}{\pi A}\right)} \quad \text{where } \lambda = \frac{\dfrac{2(C_L)_\infty}{(\theta+\alpha)}}{\pi A+2\left(\dfrac{\partial C_L}{\partial\alpha}\right)_\infty-2\pi(1+\sigma)}$$

The value adopted for C'_μ or C_μ should if possible relate to the momentum leaving the flap trailing-edge. In practice, this trailing-edge momentum may reach only 0·95 of the momentum emerging from the slot ahead of the flap, the proportion being even less (see section 4) if the slot velocity (or momentum) is derived theoretically or when the flap angle is very large. Again, the jet angle to be prescribed naturally lies between the

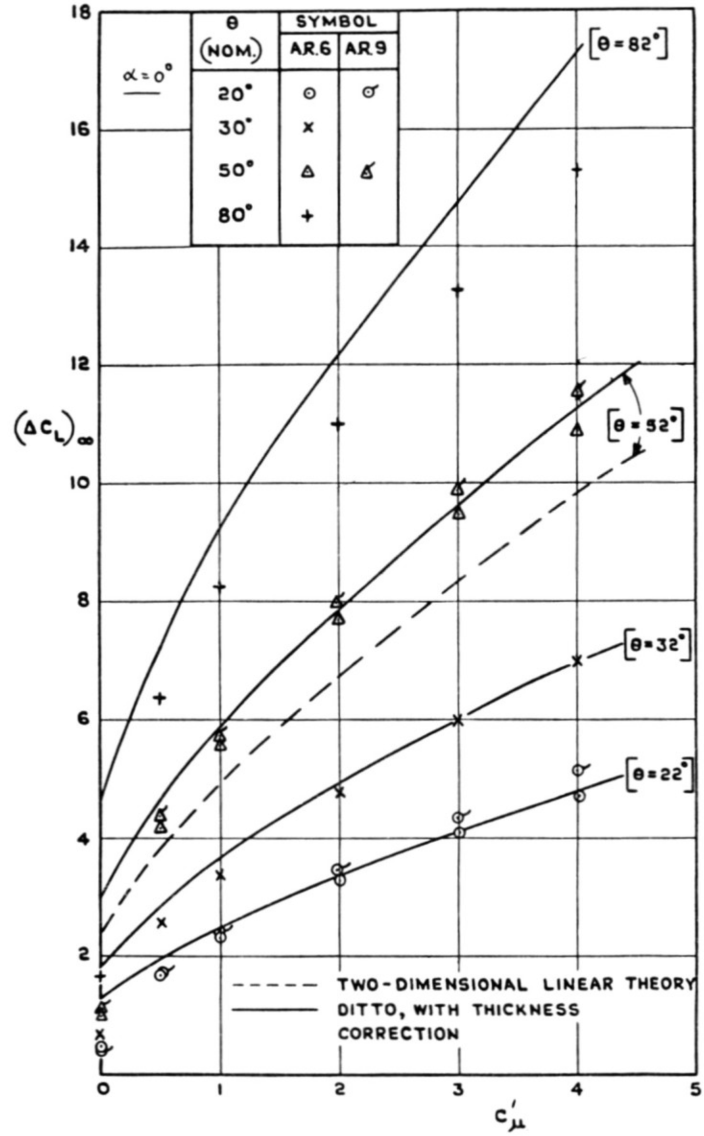

FIG. 8. Comparison of reduced experimental and theoretical values for lift increment (complete model results).

inclinations of the flap upper surface and the flap mean-line to the wing chord-line, usually closer to the former. The linearised relations can be expected to over-estimate the lift progressively as the jet angle and wing incidence are raised, as can be illustrated by comparing exact and linear-

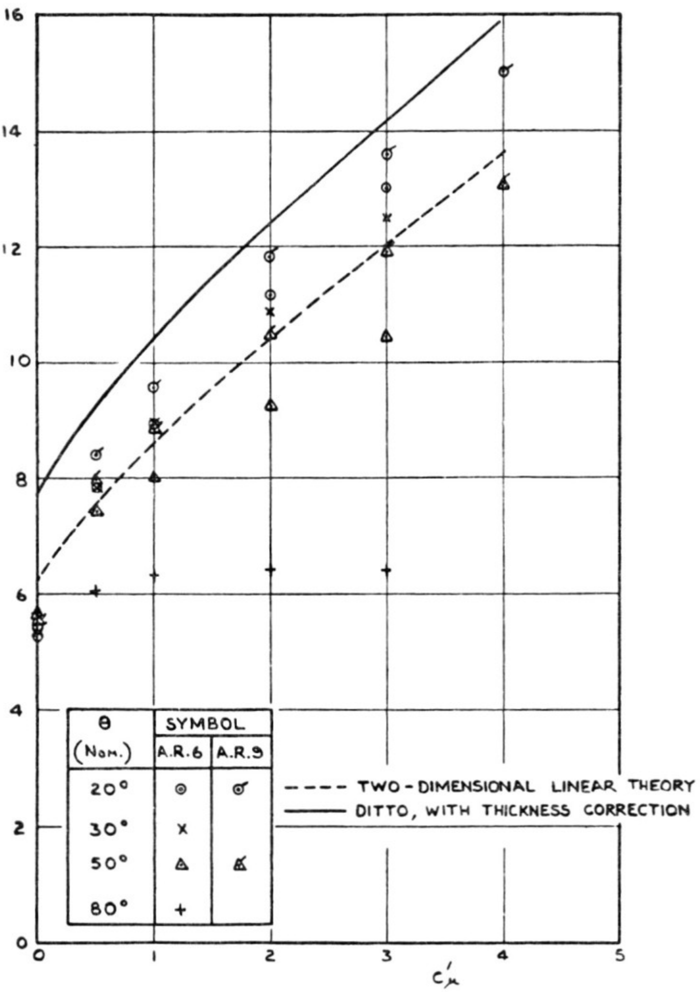

FIG. 9. Comparison of reduced experimental and theoretical values for lift-incidence curve slope (complete model results).

ised theory for a thin flat-plate with a simple trailing-edge flap. For example, with a 25% chord flap at deflections of 30° and 80°, the ratio of the lift increment given by exact theory to that from linearised theory falls from 0·95 to 0·80 respectively at zero wing incidence, while the corresponding ratio of lift-incidence curve slopes falls from 0·99 to 0·93.

To assess the validity and usefulness of the above arguments, the experimental lift results for the aspect-ratio 6 and 9 versions of the complete model have been reduced to quasi two-dimensional increments $(\Delta C_L)_\infty$ at zero incidence and lift-incidence slopes $(\Delta C_L/\Delta \alpha)_\infty$, by applying the part-span correction factors λ and ν. Figs. 8 and 9 compare these reduced experimental values against the results of two-dimensional linearised theory, both with and without the correction for thickness-chord ratio to the pressure-lift. On the basis of static force and flow measurements, the trailing-edge momentum was taken as 0·85 of the slot value derived from the measured mass-flow rate and isentropic theoretical velocity.

The experimental $(\Delta C_L)_\infty$ agrees reasonably well with the theoretical estimates (Fig. 8) up to jet deflections of about 50°, when wing thickness is allowed for, except at small C_μ-values where flow separation is present on the flap. However, it should be noted that an error of two or three degrees in the choice of jet angle for the theoretical estimates could lead to appreciably poorer agreement at low values of Θ. At large jet angles, the experimental results are, as expected, much lower than the theoretical values, though not as much as might have been argued from a comparison of exact and linearised theories for simple flaps.

The experimental results for $(\Delta C_L/\Delta \alpha)_\infty$ shown in Fig. 9 have been derived by differencing values at α of 0° and 15°. Although the agreement with the corresponding theoretical estimates allowing for thickness is reasonable at $\theta \triangleq 20°$, the experimental results fall much below the theoretical at higher angles. In an extreme case, at $\theta \triangleq 80°$, $(\Delta C_L/\Delta \alpha)$ increases very slowly with C_μ to only about 10% above its value at zero C_μ.

An analysis of the experimental results for the aspect-ratio 6 half-model leads to very similar conclusions. For project work, it would seem better to use a relation of the type (4) to interpolate or extrapolate from the available experimental results, rather than to attempt absolute prediction of lift.

3.2 *Stalling Behaviour*

Due to the large circulation generated with jet flaps, severe adverse pressure gradients can appear over the wing upper surface near the nose, even at low incidences, though the associated pressure recovery is considerably less than if the same circulation were generated by wing incidence alone. General rules for the prediction of stalling incidence with jet-flap wings are difficult to formulate, since the C_μ-value and jet deflection are important factors as well as wing shape. With wing sections of small or moderate camber and thickness, flow separation tends to occur first at the nose as the incidence is increased, but re-attachment is induced further aft by the boundary-layer control action of the jet flap. Eventually, stalling occurs when the jet induction effect is not strong enough and the flow breaks away completely from the upper surface. For example, on the half-model with a 12% thick section, the stalling incidences ($\partial C_L/\partial \alpha = 0$) rose markedly at high C_μ-values and moderate jet angles, but fell to only a few degrees at low C_μ-values and large jet angles. The nose separation can be delayed about 5° by the incorporation of a drooped leading-edge (Fig. 6*b*). However, in practice, wing nose B.L.C. by blowing (or suction) can be more powerful and profitable, applied either within the first 2% chord from the wing leading-edge or at the knee of a leading-edge flap.

Alternatively, if lower cruising speeds are acceptable, a thick highly cambered wing section (say NACA 4424) can adequately reduce flow separation over the nose at high lift coefficients, a larger thickness and camber than usual being tolerable because the incipient trailing-edge separation is controlled by the nearby jet efflux. For example, on the aspect-ratio 6 complete model, the stalling incidence rose to more than 30° with $C_\mu > 1$, an untrimmed C_L-value of 12 then being reached with $C_\mu \simeq 4 \cdot 0$ and $\Theta \simeq 50°$ (Fig. 17*a*). The stall tended to become more abrupt at the high C_μ-values, but this is not unreasonable when the flow is maintained unseparated by the thick wing and jet induction effects up to such high stalling angles and lift coefficients.

3.3 *Pitching Moments and Downwash*

The ratio ($-\Delta C_m/\Delta C_L$) of the measured increments in nose-down pitching moment and lift, due to blowing and flap deflection on the complete model at zero incidence, are compared in Fig. 10 with the corresponding values from two-dimensional linearised theory. Both experimental and theoretical values increase steadily with C_μ, confirming the expected rearward movement of the centre of lift. The experimental values, which decrease as the aspect-ratio is raised from 6 to 9, are higher than the two-dimensional theoretical values for blowing over a 10% chord flap. This also applies for the aspect-ratio 6 half-model results and would be expected from conventional arguments following lifting-line theory, which imply that the pitching-moment increment due to flap deflection is independent of aspect-ratio. As regards the variation of pitching moment with incidence, the experimental results on both the complete model and the half-model suggest an increasing value of $-(\mathrm{d}C_m/\mathrm{d}C_L)$ with increasing C_μ, i.e. a rearward movement of the aerodynamic centre, in contrast to the theoretical trend ($c_f/c = 1$ curve of Fig. 10).

The amount of trim required with practical C.G. positions (say about 0·35c) is exceptionally large at high lift-coefficients, so that a tailplane of conventional type is quite inadequate for this purpose. Fig. 11 shows that auxiliary jets, applied to provide a download at the tailplane loca-

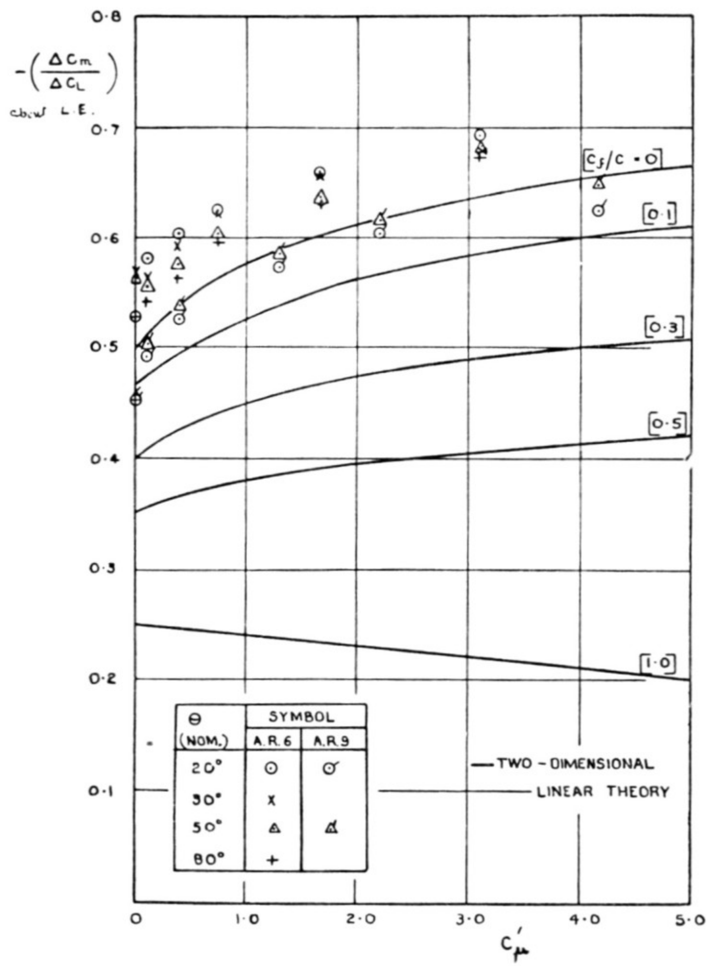

FIG. 10. Comparison of experimental $\Delta C_m/\Delta C_L$ at zero incidence with two-dimensional theoretical values (complete model results, without tail).

tion, could require a jet momentum as much as one-third of the jet-flap momentum, the trimming loss being of the order of one-tenth the wing lift. Much smaller auxiliary blowing requirements could suffice if used for B.L.C. or a jet flap on the tailplane itself. A foreplane layout is of course more attractive from the trimming aspect, but could be objectionable because of forward location of the aerodynamic centre and interference over the wing from the foreplane downwash.

Behind a jet-flap wing, the downwash is large even at a high tailplane location (Fig. 12). Both ε and $\partial\varepsilon/\partial\alpha$ tend to increase steadily with C_μ.

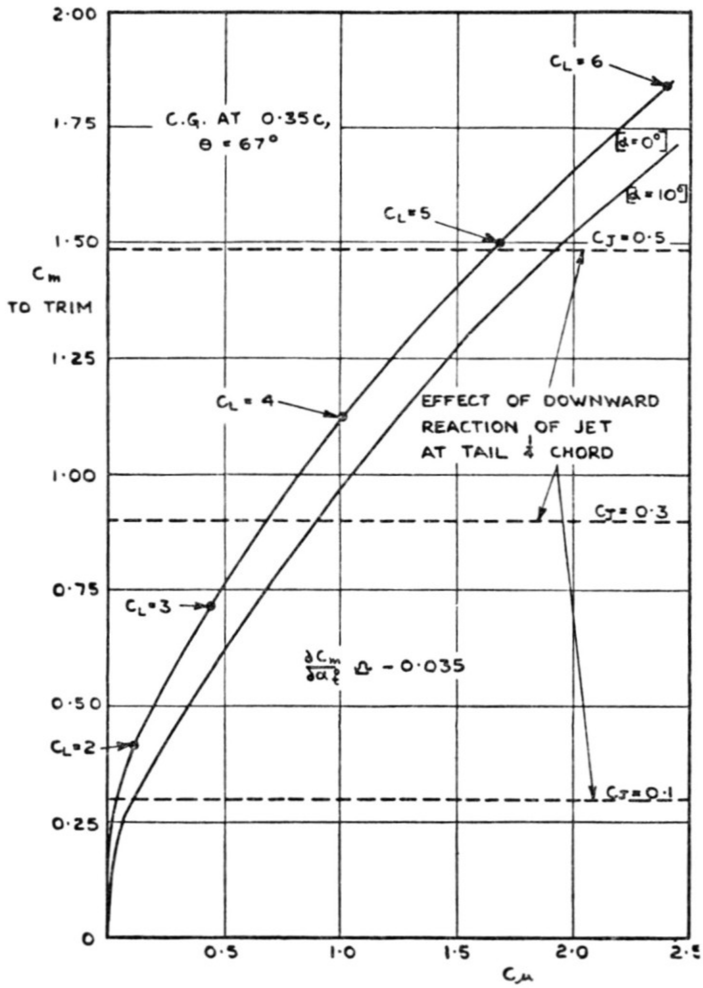

FIG. 11. Pitching moment to trim with zero tailplane lift (aspect-ratio 6 half-model).

For example, on the aspect-ratio 9 complete model with $\theta \triangleq 50°$ and $\alpha = 10°$, the downwash measured at $l_t = 4{\cdot}1\ \bar{\bar{c}}$ aft of the wing mean quarter-chord point and $h_t = 1{\cdot}5\ \bar{\bar{c}}$ above the extended wing-chord line rises from 7° to 20° as C_μ is increased from 0 to 2, while $(1-\partial\varepsilon/\partial\alpha)$ falls from 0·75 to 0·4 (see Fig. 18*a*). In the application of linearised theory for the estimation of downwash, considerable care is needed and some difficulties are encountered with regard to the choice of the effective jet path and tail height, as well as of the appropriate C_μ or C_L.

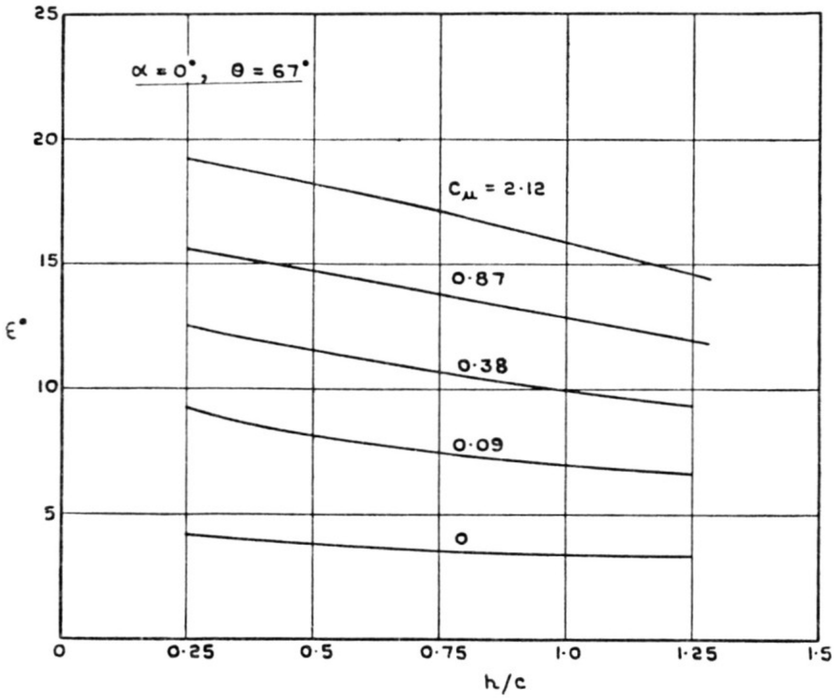

FIG. 12. Variation of downwash with tailplane height (aspect-ratio 6 half-model).

4. THRUST AND DRAG

The thrust coefficient given by linearised inviscid flow theory for full-span jet-flap wings becomes

$$C_T = C_\mu - C_L^2/(\pi A + 2C_\mu) \tag{5}$$

where the last term on the right represents the "trailing vortex" drag associated with an elliptic spanwise distribution of loading. To examine the practical deficiency in thrust, a more general form of (5) can usefully be considered, say

$$C_T + C_{D0} = rC_\mu - k \cdot \phi \tag{6}$$

Here, the "sectional thrust" is for convenience expressed as a proportion r of the theoretical value C_μ, while the drag associated with finite aspect ratio effects is expressed as a proportion k of the theoretical value $\phi[\equiv C_L^2/(\pi A+2C_\mu)]$. The term C_{D0} represents the drag at zero-lift, without flap deflection and blowing, as usual.

Even at small incidences and jet angles when variation of k from the datum theoretical value of unity is not significant, or at zero forward speed, the sectional thrust factor r falls below unity for a variety of reasons. Firstly, due to boundary-layer growth in the slot, the jet momentum $M_J V_J$ is usually over-estimated. For example, on the half-model, the true (measured) mass-flow rate is only 0·96 of the theoretical based on the geometrical slot area, this deficiency being explicable in terms of the boundary layer displacement thickness. Thus the effective jet momentum and sectional thrust factor r on this model is unlikely to exceed 0·93 of the theoretical, if no allowance is made for the momentum deficiency due to boundary layer growth, or 0·97 if only V_J is determined theoretically and M_J is given its measured experimental value. Further deficiencies can occur if blockage is introduced into the slot, over and above that due to the lower mass-flow rate associated with the smaller slot exit area at a prescribed pressure ratio. For instance, on the half-model, spacers 0·25 in. wide located at spanwise intervals of 2 in. along a slot of 0·08 in. depth led to a decrease of 0·015 in r, though doubling the spacer size made the decrease only 0·02. Again, the flow entrained locally into the jet efflux can produce suction drag on the rearward-facing surfaces of the slot lips, but model results indicate that the corresponding reduction in r is unlikely to exceed 0·01 provided the lip thickness is no larger than twice the slot width.

When the air is ejected over a trailing-edge flap, further deficiencies in thrust can arise from the high skin friction on the flap upper surface. Typically, on model scale, the reduction in r is about 0·05 for a flap/wing chord ratio of 5%, rising only to 0·06 for a 10% chord flap. Unfortunately, the relative importance of slot width is not known. Direct impingement of the jet on the flap nose can also be detrimental. Model results indicate that r can be reduced as much as 0·03, if the upper surface of the flap nose is aligned with the upper boundary rather than the lower boundary of the jet. On the other hand, exploratory studies suggest that a small gap between the flap nose and the lower lip of the slot, roughly equal to the slot width, can be beneficial since some mixing with the mainstream air passing through this gap occurs at the lower boundary of the high velocity jet, before the latter reaches the flap upper surface.

Inclination of the jet sheet to the mainstream direction by flap deflection or wing incidence, tends to reduce the sectional thrust factor r because of mixing and turning losses and, to a lesser extent, because of "lift-dependent" drag associated with boundary-layer growth over the main aerofoil. With finite-span wings, significant variations may also arise in the finite aspect-ratio drag factor k over the full practical range of jet deflection angle and momentum coefficient. In the absence of comprehensive and accurate force measurements on two-dimensional blowing configurations or over a wide range of aspect ratios, analysis of available results must be regarded as an expedient for providing rough

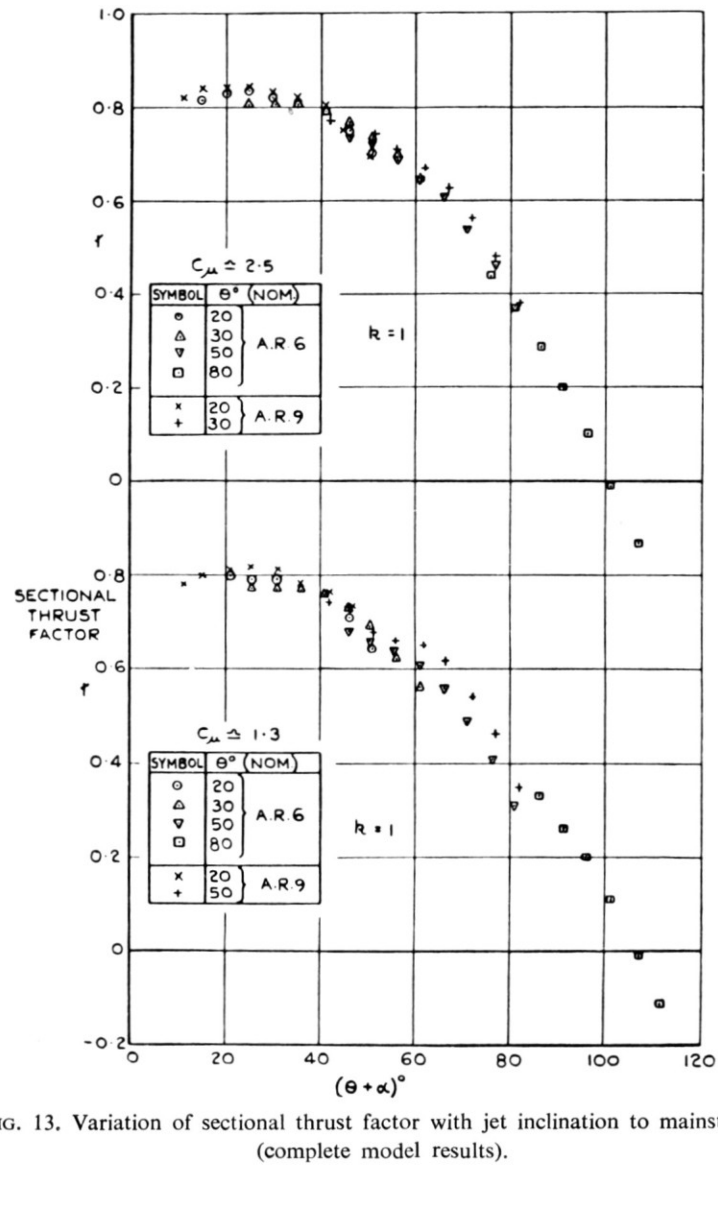

FIG. 13. Variation of sectional thrust factor with jet inclination to mainstream (complete model results).

working rules for limited projected work, rather than by way of justification of fundamental concepts. Certainly, the relation (6) grossly overestimates the thrust results for the half-model and the complete models at appreciable jet-deflection angles if r and k are assigned unit theoretical values, or even experimental values corresponding to small angles of incidence and flap.

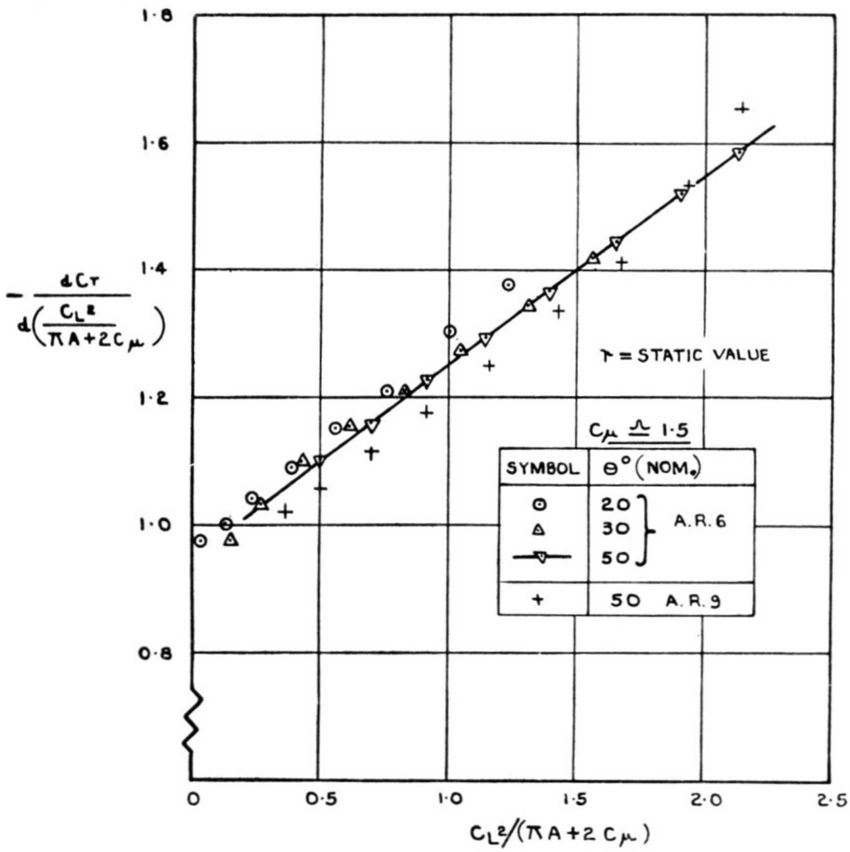

FIG. 14. Variation of finite aspect-ratio drag factor (complete model results).

One simple approach is to assume that the deficiencies in thrust are primarily sectional in nature ($r < 1$) and that the "trailing-vortex" drag is adequately predicted by theory ($k \triangleq 1$) for practical purposes. Figure 13 shows the consequent variation of r with $(\Theta + \alpha)$ at C_μ-values about 1·3 and 2·5 for the complete model. The reasonable correlation of the aspect-ratio 6 and 9 results lends support to this method of analysis, at least for $C_\mu > 1$. The value of r reaches only about 0·83 on this model, even at small angles, but could be as high as 0·92 with improved slot design and flap alignment, along the lines discussed earlier. If the flap were of the retractable type, providing a good T.E. slot configuration without jet deflection, the value could rise to 0·97 under such conditions (say at cruise), thus comparable with that for a conventional round nozzle. For $(\Theta+\alpha)$ values above 30°, the complete model results give r-values decreasing steadily from 0·83 to about 0·65 and 0·25 at $\theta+\alpha \simeq 60°$ and 90° respectively.

An alternative approach is to assume that r takes values given by static measurements of resultant thrust (including turning losses), so that any additional thrust deficiencies must be primarily accounted for by treating k as a function of ϕ. Again, such an analysis seems reasonable since plots of C_T against C_μ at constant values of $\varphi[\equiv C_L^2/(\pi A+2C_\mu)]$ give a series of straight lines, nearly parallel and of slope roughly equal to the corresponding static values of r, namely 0·83 and 0·80 at $\theta \simeq 20°$ and 50° respectively. Figure 14 shows that k (ϕ) increases noticeably and almost linearly with ϕ, but the analysis tends to break down for high jet deflection angles and C_μ-values. Of course, it can be argued that the variation of k (ϕ) would be much smaller if the lift-dependent drag, arising from boundary-layer growth over the forward part of the aerofoil, were taken into account by the introduction of a further semi-empirical term into (6).

With a part-span jet flap, additional lift-dependent drag must arise because of the departure from the optimum spanwise lift distribution. There is, at present, no reliable theory for predicting such increments, which can become significant even at moderate C_μ-values and jet deflections.

5. SIDESLIP DERIVATIVES

As regards lift, thrust, downwash and longitudinal stability derivatives, the influence of moderate amounts of sideslip can probably be ignored, though there is some evidence that tailplane power may be reduced noticeably. On the other hand, estimation of lateral stability derivatives for jet-flap wings by simple conventional arguments is unlikely to be adequate. To provide some basic data and understanding, measurements of lateral derivatives and flow visualisation experiments were carried out on the R.A.E. complete model, with individual variation of aspect-ratio (6 to 9), sweepback (0 to 10°) and dihedral (−1° to 4°). These brought to light some novel aspects, of vital importance from lateral stability considerations.

First of all, the positive l_v-values (anhedral effect) found on the aspect-ratio 6 version at high jet-deflections and lift coefficients (Fig. 15*a*) are not predicted by conventional arguments. Furthermore, the positive increment in l_v to be expected with increasing aspect-ratio becomes especially large at the high C_L's. Such planform effects can be explained qualitatively by modifications to conventional theory, taking into account positive contributions from the bound vorticity distribution associated with the large effective camber (at zero lift) and from the powerful trailing

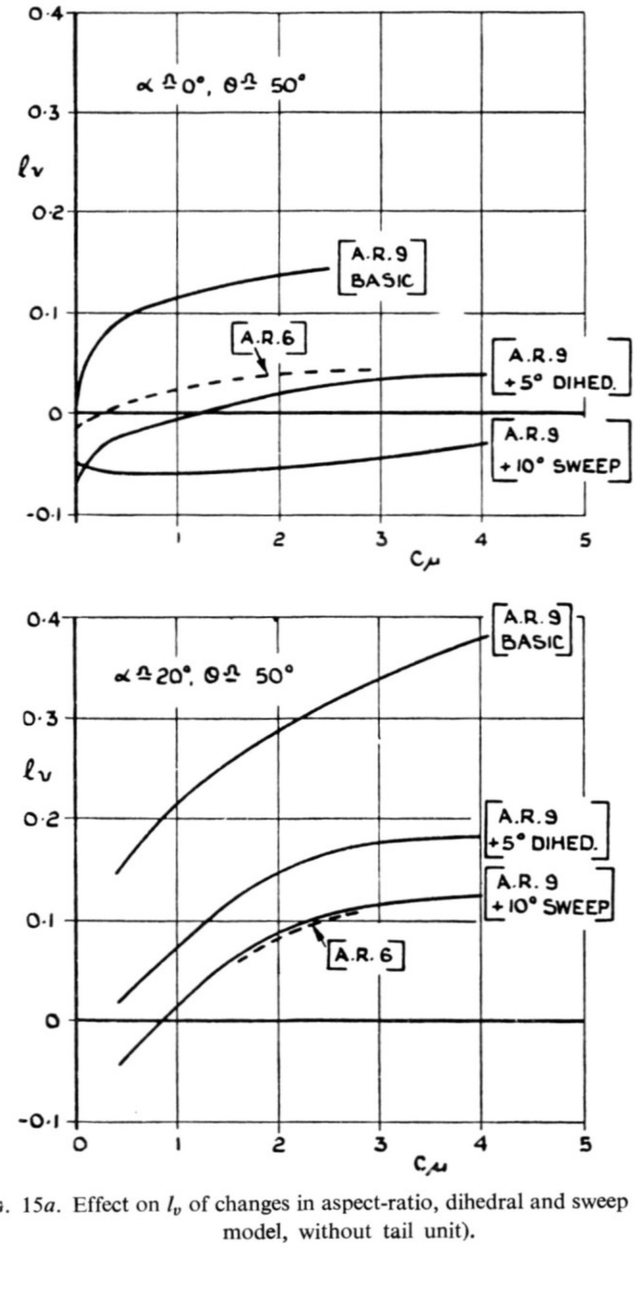

FIG. 15*a*. Effect on l_v of changes in aspect-ratio, dihedral and sweep (complete model, without tail unit).

vortex sheet*, together with the large increase in lift-incidence curve slope (as well as C_L) at high C_μ. Unfortunately, since for spiral stability, $(l_v n_r - n_v l_r) > 0$, it is usually desirable not only for l_v to be negative, but also to become increasingly negative with increasing C_L, unless some of the other derivatives are artificially controlled.

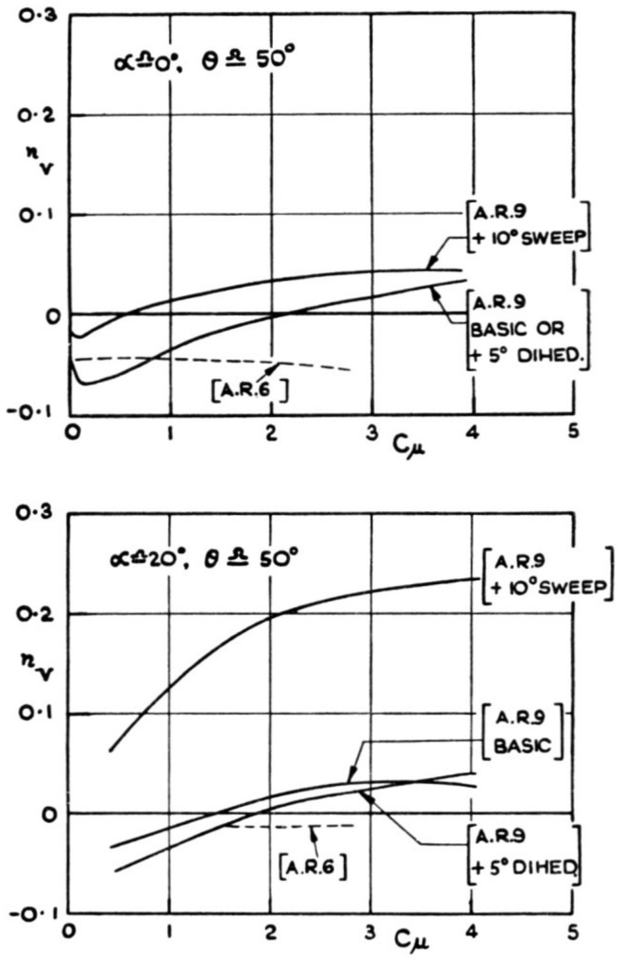

FIG. 15*b*. Effect on n_v of changes in aspect-ratio, dihedral and sweep (complete model, without tail unit).

As expected, dihedral can give a reduction in l_v, but not as much as desired at high C_L's. The reduction can be reasonably predicted by conventional theory, provided the large variation in lift-incidence curve slope with C_μ is taken into account. Sweepback also causes a substantial reduction (Fig. 15*a*), but this does not grow steadily in magnitude with

* This approach was first put forward by staff of Hunting Aircraft Ltd.

C_L as would be expected from conventional arguments. Again, qualitative predictions can be provided by modifications to conventional theory considering the lifting effectiveness of jet-flap aerofoil sections normal to the quarter-chord line (or T.E. flap hinge line). However, adequate theoretical methods for the satisfactory estimation of l_v are not yet avail-

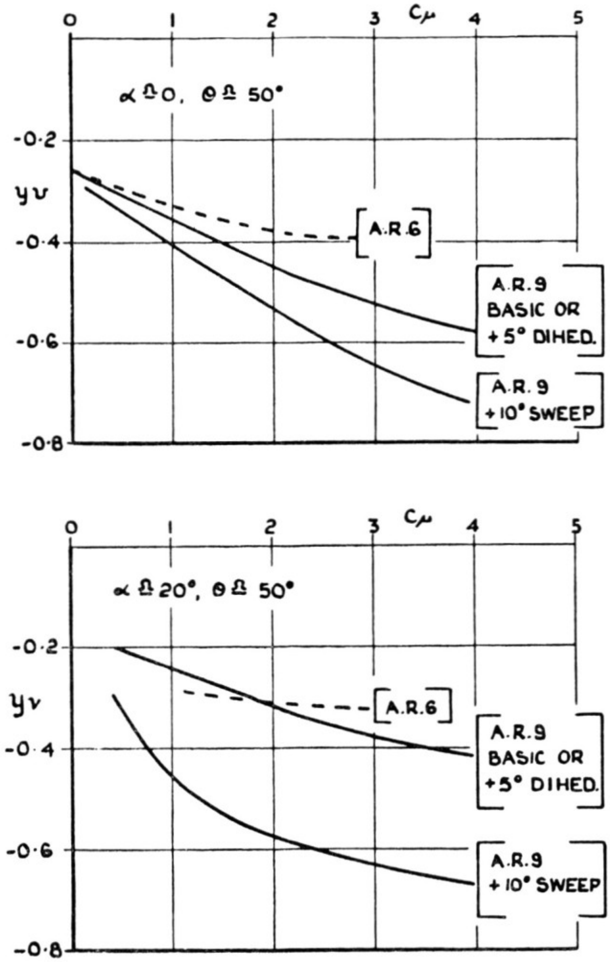

FIG. 15c. Effect on y_v of changes in aspect-ratio, dihedral and sweep (complete model, without tail unit).

able, particularly as regards the variation with C_μ, incidence, or jet angle, so that semi-empirical treatments have still to be used. Moreover, sweepback can also cause substantial increases in the yawing moment derivative n_v and the side-force derivative $-y_v$ (Figs. 15b and 15c). These increases are generated primarily by sidewash variations over the fuselage; at the same time, the fin contribution tends to increase.

Dynamic derivatives for jet-flap wings have so far been evaluated by quasi-steady treatments, and it has been argued that these should suffice for most stability calculations. Only by experimental measurements of such derivatives under oscillatory conditions can it be ascertained whether periodic variations in the trailing vorticity can introduce phase lags of practical importance.

6. EFFECT OF GROUND

The lift on a jet-flap aerofoil near the ground rises much as usual with increasing C_μ or jet angle Θ, until the jet actually impinges on the ground and effectively blocks the mainstream flow between the aerofoil lower surface and the ground. With further increase in C_μ (or Θ), a vortex forms below the aerofoil and generates downward suctions on the rear lower surface. This not only limits further rises in C_L (Fig. 16),

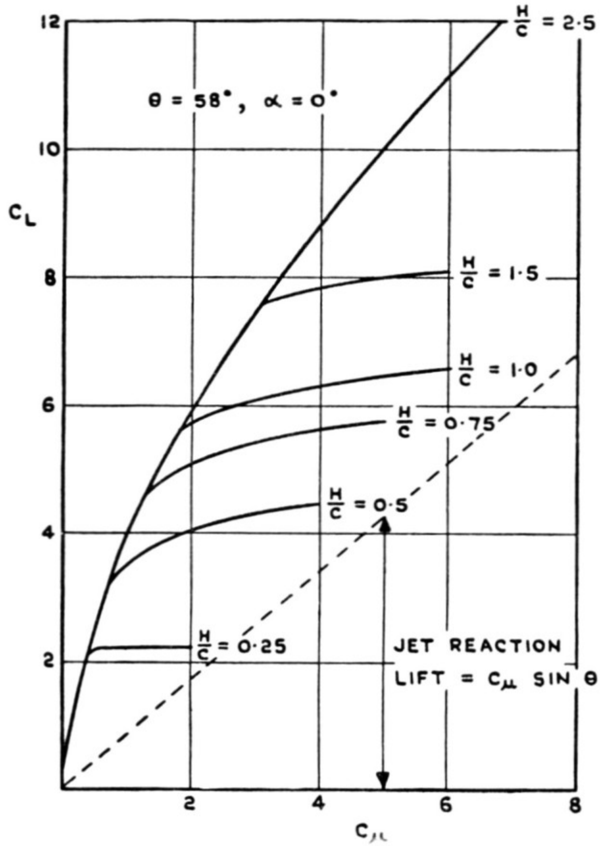

FIG. 16. Effect of ground on C_L vs. C_μ curve (two-dimensional model with T.E. blowing).

by reducing the pressure-lift C_{Lp}, but also leads to rapid forward movement of the centre of lift (pitch-up) and can cause substantial changes in thrust. Typically, at a ground clearance of unit chord, this unfavourable ground effect becomes noticeable when C_μ reaches about $1\frac{1}{2}(C_L \simeq 5)$ for jet angles θ of the order of 60°. However, when the

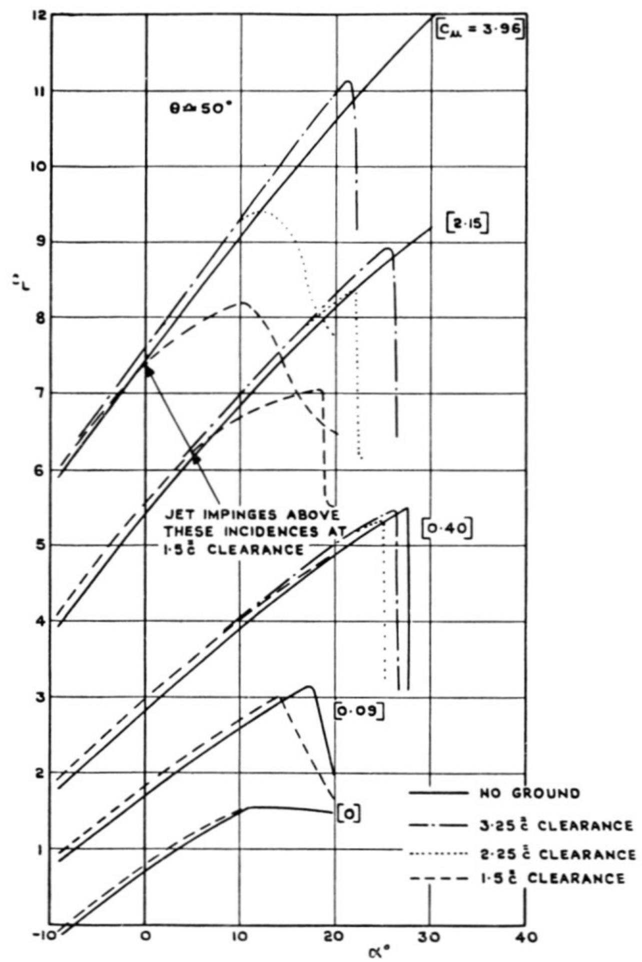

FIG. 17*a*. Effect of ground on lift-incidence curves (aspect-ratio 9 complete model, without tail).

clearance is raised to two chords, the effects appear to be negligible for C_μ values up to at least 4 $(C_L \simeq 10)$ for the same value of θ.

With finite aspect-ratio wings, the effects of ground proximity are naturally more complicated than under two-dimensional conditions, but again the amount of interference with the jet path is the deciding factor. The nature and magnitude of ground interference effects can be conveniently discussed in the light of the experimental studies on the unswept aspect-ratio 9 version of the complete model (with 4° dihedral).

Before impingement occurs, the lift at incidences well below the stall is slightly increased by ground proximity, as normally expected (see Fig. 17*a*), while the effects on pitching moment and thrust are also not serious

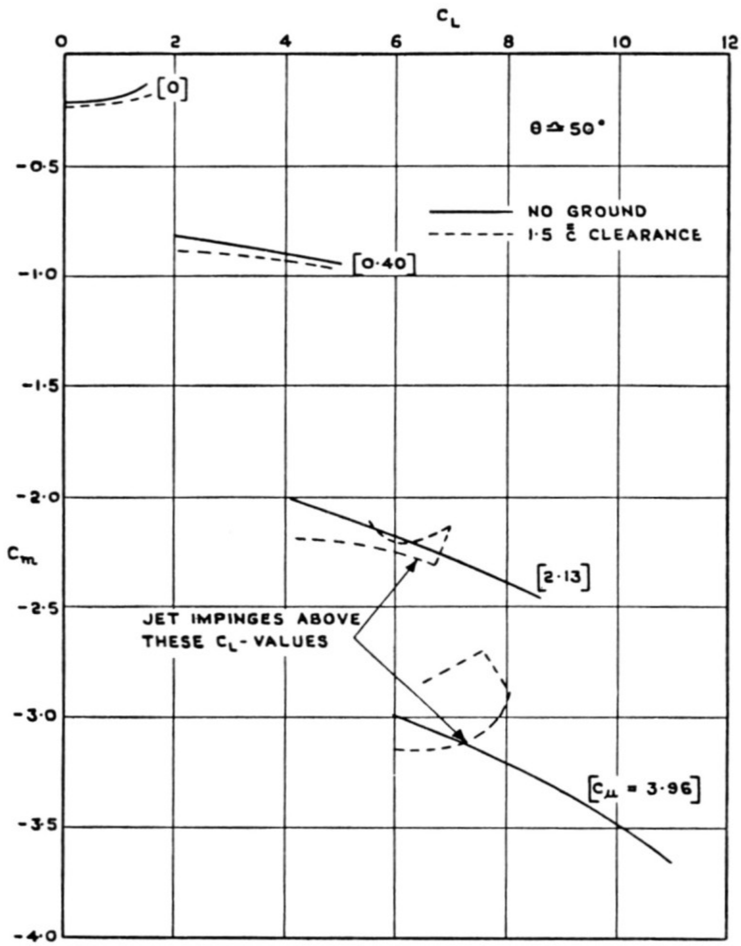

FIG. 17*b*. Effect of ground on pitching moment-lift curves (aspect-ratio 9 complete model, without tail).

(Figs. 17*b* and 17*c*). Moreover, the stalling incidence decreases only a few degrees as the ground clearance is reduced and the nature of the stall does not alter, starting with separation of the turbulent boundary-layer just ahead of the blowing slot at the wing root. The sideslip derivatives are also not significantly affected. In contrast, the downwash at a conventional tailplane position ($l_t/\bar{\bar{c}} = 4{\cdot}1$) is much reduced by ground effect, even well before impingement takes place and at a substantial tailplane height ($h_t/\bar{\bar{c}} = 1{\cdot}5$) above the extended wing chord line (see Fig. 18*a*).

When the C_μ-value or jet inclination is sufficiently large to cause jet impingement, the lift falls below the value achieved without ground, the lift-incidence curve slope also falls markedly with further increase in

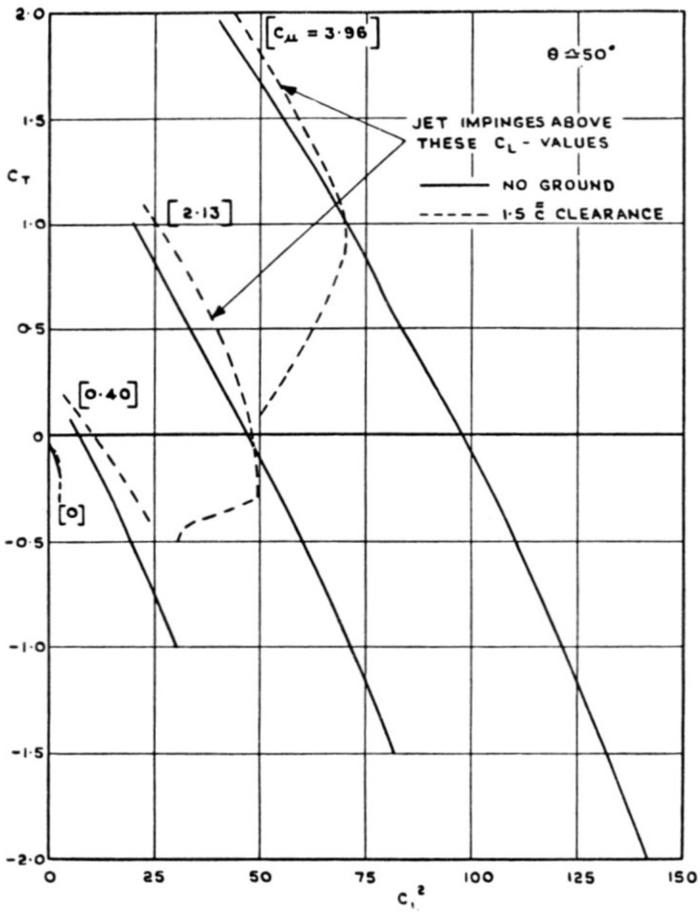

FIG. 17*c*. Effect of ground on thrust-lift curves (aspect-ratio 9 complete model, without tail).

incidence, and the stall occurs much earlier as the ground clearance is further reduced (Fig. 17*a*). Flow studies show that, on impingement, some of the jet flows forward along the ground until the mainstream flow forces it to separate; the separated air then flows spanwise out towards the wing tip and part is entrained back into the jet efflux to form a vortex (Fig. 19). Some mainstream air is still able to pass between the wing and the vortex and mix with the jet efflux leaving the wing trailing-edge. With increasing incidence, the point of impingement moves forward, partly because the jet inclination $(\Theta+\alpha)$ increases and partly because the trailing-edge moves closer to the ground. Simultaneously, the vortex grows in strength and size, diverting more and more mainstream air over and around the wing, until the mainstream flow is unable

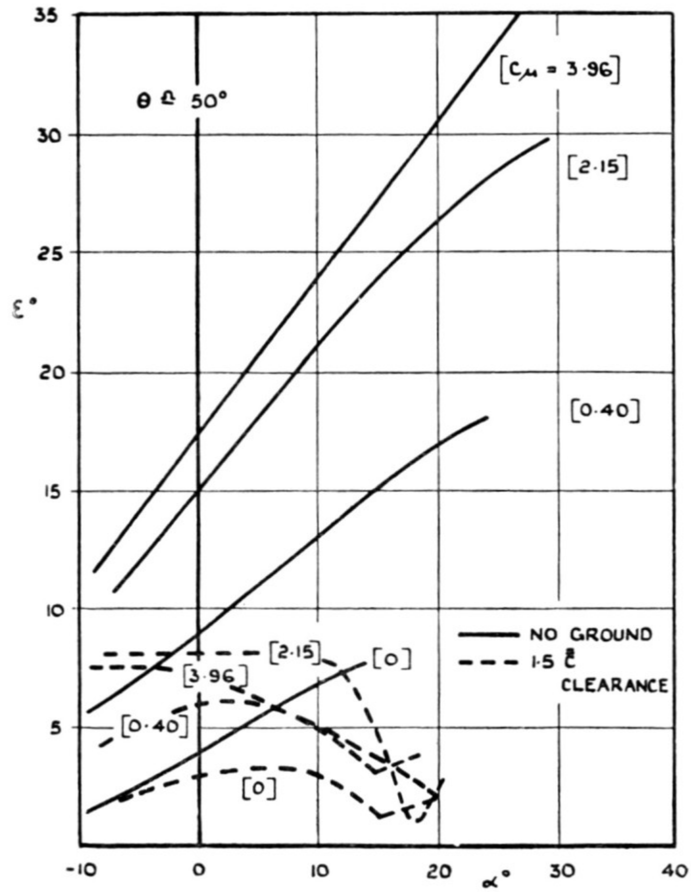

FIG. 18*a*. Effect of ground downwash-incidence curves (aspect-ratio 9 complete model).

to penetrate between the wing lower surface and the ground, except possibly at its outer edges. Pressure distributions indicate that impingement causes a general reduction in sectional lift (circulation), except near the wing tips. The normal rearward movement of the front stagnation point (lower surface) with increasing incidence is inhibited (Fig. 20), so that the peak suctions on the upper surface rise more slowly because of ground effect (Fig. 21). The loss in lift due to ground is thus not primarily associated with lower surface suctions, as has been suggested for the two-dimensional aerofoil at zero incidence, possibly because of the "spanwise venting" which can occur with a finite span jet sheet.

The nature of the wing stall can also be changed by impingement, a trend towards leading-edge separations being promoted on the complete model.

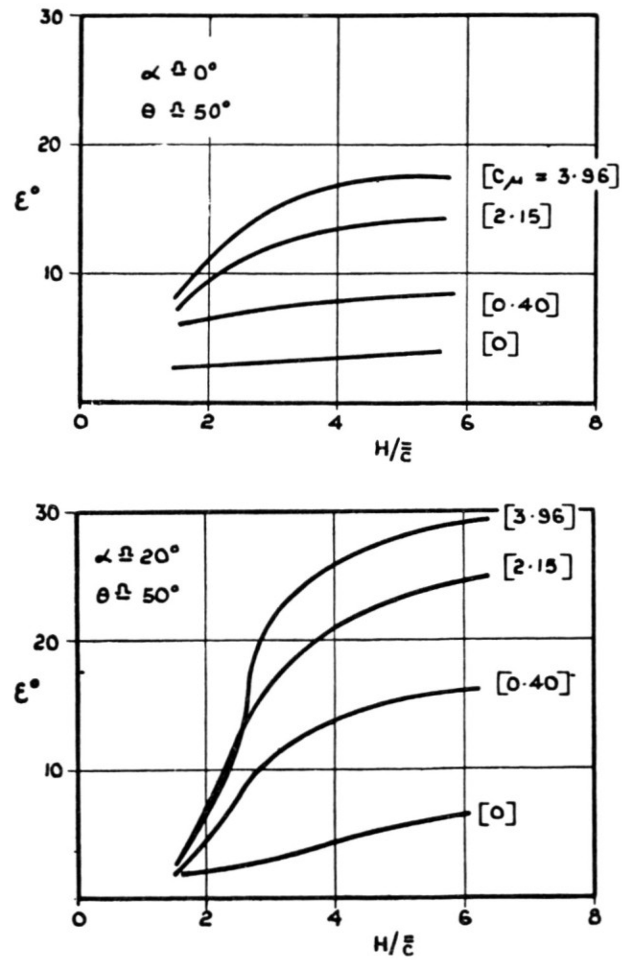

FIG. 18*b*. Variation of downwash at tail with ground clearance (aspect-ratio 9 complete model).

The rounding of the lift incidence curves when impingement occurs is also accompanied by a tendency to pitch-up (tail-off) and some decrease in thrust (Fig. 17). The usual increase of downwash with incidence disappears completely (Fig. 18*a*), and the variation of downwash with ground clearance is considerable (Fig. 18*b*). Fortunately, the sideslip derivatives are less seriously affected by impingement. Some reductions occur in the yaw derivative n_v and the sideforce derivative $-y_v$, and are accompanied by smaller sidewash at the fin position, presumably because the jet path passes much nearer to the fuselage and fin. However, the roll derivative l_v tends to become more negative, corresponding to greater dihedral.

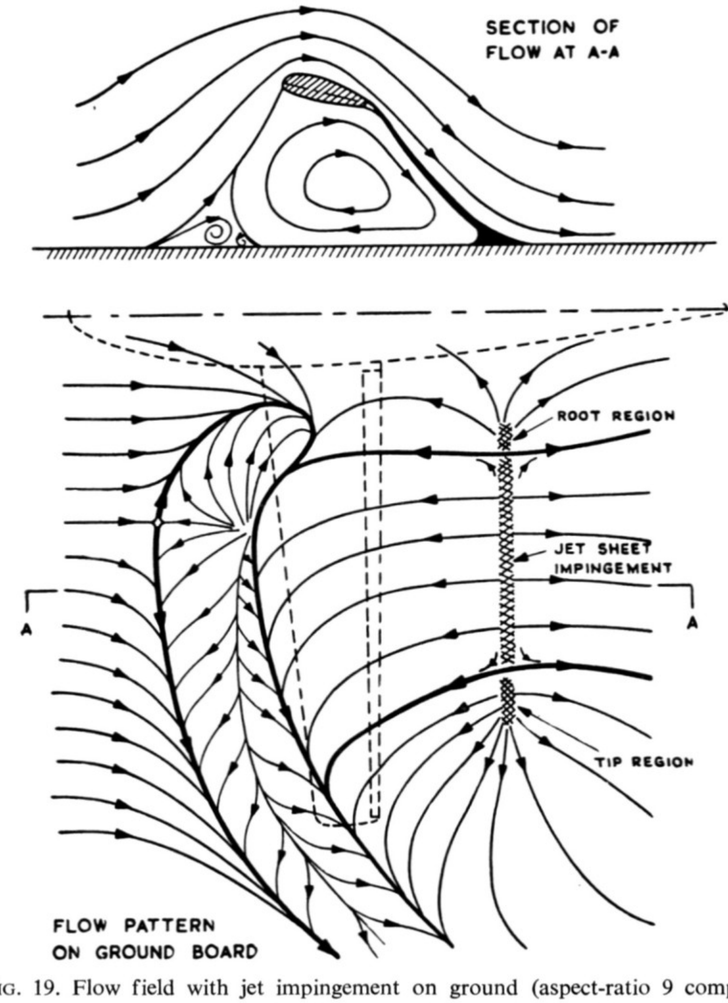

FIG. 19. Flow field with jet impingement on ground (aspect-ratio 9 complete model, $\alpha = 15°$, $C\mu = 2{\cdot}1$, $H/\bar{\bar{c}} = 1{\cdot}5$, $\Theta \simeq 50°$).

It should be remarked that, since the present wind-tunnel experiments were carried out with a boundary-layer on the fixed ground-board, the effects due to ground may be exaggerated. But the qualitative features at least seem justified and must be borne in mind as limiting factors on take-off and landing performance. Although some simple mathematical representations of ground effect have been formulated for the two-dimensional aerofoil, there is as yet no adequate theoretical treatment for jet-flap wings with the jet in close proximity to or impinging on the ground.

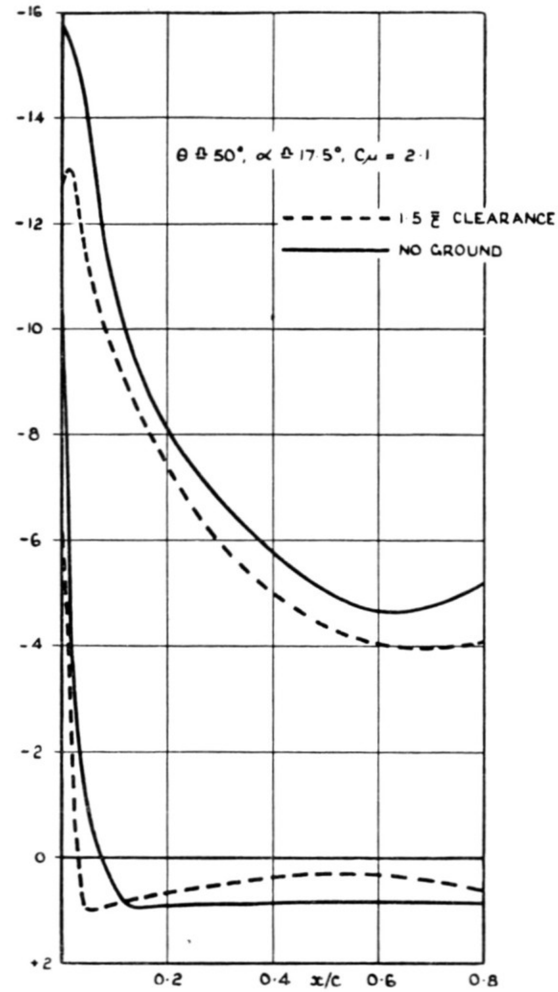

FIG 20. Effect of ground on mid-span pressure distribution (aspect-ratio 9 complete model).

7. CONCLUDING REMARKS

The aerodynamic principles of jet-flap wings are now well established, at least in steady motion, as a result of recent detailed wind-tunnel and theoretical investigations. Useful estimates can now be made of lift, pitching moment, downwash, thrust and lateral stability derivatives for wings of

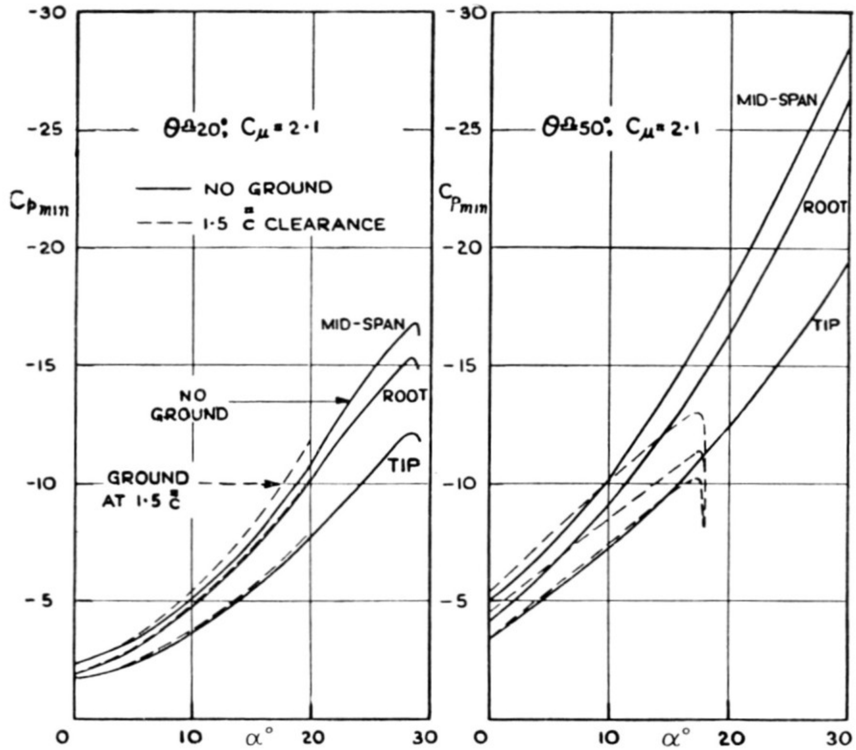

FIG. 21. Effect of ground on growth of peak suction with incidence (aspect-ratio 9 complete model).

moderate aspect-ratio, sweep and full-span jet deflection. Unfortunately, although the available aerodynamic theories have provided valuable background, they are essentially simple thin aerofoil and lifting-line treatments assuming inviscid flow. The influence of viscosity, together with the marked divergence of the jet sheet from the wing plane, cannot generally be ignored. Thus, semi-empirical approaches have still to be used, particularly as regards the estimation of thrust and downwash with large jet deflections and the effects of part-span blowing or spanwise variation of jet angle. In addition, available simple theories on the effects of sideslip and proximity to the ground at most only give qualitative results over a limited range of parameters. Clearly, there is scope for further experimental and theoretical research on many other aspects, for example the reduction of deficiencies in thrust associated with skin friction, turning and mixing of the jet, and on the determination of oscillatory derivatives.

Performance and stability studies have naturally provided much useful guidance as to the aerodynamic features of major importance for jet-flap aircraft designs. With the recent development of turbo-jet engines of high bypass ratio and of light-weight units as gas-generators, mixed jet-flap/round-jet configurations have become attractive for short take-off and landing, the jet flaps being used primarily for lift and the conventional round nozzles for thrust. Again, jet flaps might usefully be incorporated to lower the transition speed of new types of VTOL aircraft, or to simplify the lifting rotor and improve helicopter performance at all speeds. Such considerations introduce many new and interesting aerodynamic problems, worth further study from both fundamental and practical aspects.

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