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# On the Effect of Fan and Thrust Engine Loading on the Transition Power Requirements of a Fan Wing

*By*

N. Gregory, M.A.

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# On the Effect of Fan and Thrust Engine Loading on the Transition Power Requirements of a Fan Wing

- By -
N. Gregory, M.A.

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SUMMARY

The ideal power requirements of a fan wing in transition have been calculated and the effects are shown of varying the fan and thrust engine areas relative to that of the wing, and of varying the wing aspect ratio. Comparison with wind-tunnel results confirms the presence of adverse jet/mainstream interaction effects neglected in the calculations.

## 1. Principal Notation

| | |
|---|---|
| $A_F$ | fan annulus area |
| $A_T$ | thrust actuator area |
| $A_W$ | wing area |
| $\alpha$ | incidence |
| D | drag |
| L | lift |
| P | fan power output |
| $V_T$ | forward speed |
| $V_F$ | fan efflux speed |
| $1/\sqrt{C_L}$ | forward speed parameter, where |
| $C_L$ | $L/\frac{1}{2}\rho A_W V_T^2$ |

ξ/

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$\xi$ ideal output power ratio, the fan's rate of doing work on the fan efflux relative to the aircraft plus the thrust engine's rate of doing work on the slipstream, divided by the hovering value of the former when supporting the same weight of aircraft at zero incidence

$\xi_1$ modified ideal output power ratio, with the denominator restricted to the condition $A_F/A_W = 0.023$, the numerator allowing for other values of $A_F/A_W$.

Suffices

$\alpha$ refers to forces arising from the circulation appropriate to incidence $\alpha$

i induced

o hovering.

## 2. Introduction

In Ref. 1, whose notation is followed here, a method was given for representing the results of wind-tunnel tests of fan wings in a non-dimensional form suitable for the analysis of transition motions. The method was illustrated by the display of the results of tests of a rectangular wing of aspect ratio 1 with a fan of area $A_F/A_W$ equal to 0.023 located at 0.354 chord[2]. The results showed various features that were thought to be peculiar to the particular values of the relevant parameters of that wing, especially to the low value of $A_F/A_W$ used, which was much less than would normally be considered for a fan-wing design.

The present calculations were undertaken to ascertain:-

(i) to what extent the previous results were influenced by the aerodynamic interactions between the efflux and the mainstream, which are frequently neglected in design studies and which were thought to be particularly severe on this wing on account of the low value of $A_F/A_W$.

(ii) how transition power requirements (neglecting the effects of efflux and mainstream interaction) would be affected by variation of fan and thrust engine loadings relative to that of the wing (which are inversely proportional to the area parameters $A_F/A_W$ and $A_T/A_W$ where $A_T$ is the area of the thrust engine "actuator disk").

(iii) how transition power requirements in a particular case (again neglecting the effects of efflux and mainstream interaction) would further be affected by variation of aspect ratio from the value of unity used in the experiments. The object here was to discover whether, at low forward speed and high incidence, variation in the induced drag could have an appreciable effect on the performance of the system.

## 3. The Effects of Aerodynamic Interactions

The variation of the ideal output power ratio with forward speed parameter and incidence is shown in Fig. 1 (taken from Ref. 1), and has been calculated from the test results obtained in the wind tunnel on the assumption that thrust actuator disk area was equal to the fan area, both being equal to 0.023 times the wing area.

In Fig. 2 are shown the corresponding curves for power requirements based on the assumption that there is no interaction between the jet efflux and the mainstream. The calculation is based on the wind-tunnel measurements and the procedure is the first one described in the Appendix.

Comparison of Figs. 1 and 2 reveals that for the particular conditions $\frac{A_F}{A_W} = \frac{A_T}{A_W} = 0.023$, neglect of the aerodynamic interference removes the hump in the power requirements between hover and fan-off conditions that is actually present at incidences $\leqslant 6°$, but that it remains true that the power requirements diminish more rapidly with increasing forward speed the higher the incidence at which transition is carried out (at any rate as far as +12°, the highest incidence at which the basic wind-tunnel data was obtained).

## 4. The Effect of Fan and Thrust Engine Loadings

The calculations of the previous section have been repeated assuming more lightly loaded lifting fans and thrust engines. The following table shows the area ratios of the cases treated.

| | | $A_F/A_W$ | | | | |
|---|---|---|---|---|---|---|
| | | 0.023 | 0.046 | 0.091 | 0.365 | 0.73 |
| $\frac{A_T}{A_W}$ | 0.023 | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 0.091 | | | ✓ | ✓ | ✓ |
| | 0.365 | | | | ✓ | |

A modified ideal output power ratio $\xi_1$ has been calculated, which is defined as the ratio of the total output power at forward speed to the hovering value of the power output at zero incidence for the wing with $A_F/A_W$ equal to 0.023. The variation of $\xi_1$ with forward speed parameter $1/\sqrt{C_L}$ is shown in Fig. 3 for various values of $A_F/A_W$ when $A_T/A_W$ is 0.023, in Fig. 4 for various values of $A_F/A_W$ when $A_T/A_W$ is 0.091, and in Fig. 5 for various values of $A_T/A_W$ when $A_F/A_W$ is 0.365.

Figs./

Figs. 3 and 4 reveal the expected reduction in hovering power with reduction in the fan loading, but show that this is offset by the appearance of a peak power demand which is significantly greater than the hovering power for values of $A_F/A_W$ greater than about 0.1. This peak power requirement is worse, the higher the thrust engine loading (i.e., for small values of $A_T/A_W$) and arises from the high peak value of momentum drag that occurs at an intermediate stage in transition when the fan is lightly loaded. Large values of $A_F/A_W$ are desirable in a lifting fan system if the same basic power plants are used both to drive the fans and to produce the forward thrust in wing-borne flight, in order that the hovering power requirements be not excessively greater than those of forward flight. Provision of some means of deflecting the fan efflux aft would then appear to be essential in order to avoid the peak power requirements.

In the case of a reasonably large value of $A_F/A_W$, Fig. 5 (plotted for $A_F/A_W$ equal to 0.365) shows that the peak power requirement is more significantly affected by reduction in thrust engine loading than the fan-off power requirement. This occurs because the large momentum drag values associated with the peak power requirements occur at a relatively low forward speed where the thrust engine is a less efficient device for producing thrust. Note that transition at 12° incidence still requires a lower maximum power demand than transition at any lower angle of incidence. With $A_F/A_W$ and $A_T/A_W$ both equal to 0.375, the peak has practically vanished, but this condition represents an absurdly low thrust engine loading. In practice, this could probably only be met with a tilting propeller system, in which case the facility for variable tilt would of itself have avoided the peak value of momentum drag.

5. <u>The Effect of Aspect Ratio</u>

The calculation of the ideal output power ratio for the wing with

$$\frac{A_F}{A_W} = \frac{A_T}{A_W} = 0.023$$

was repeated by the second technique described in the Appendix. The result of the calculations is shown in Fig. 6, which may be compared with the earlier calculations of Fig. 2. Although the new calculations are more soundly based than the earlier ones, they are less accurate in that the inclinations of the fan axis to the vertical and of the thrust producing axis to the horizontal which occur when the wing is at incidence have been ignored. The results of the two sets of calculations are not identical, but they reveal the same trends with incidence. For the discussion of the present paragraph, comparisons will therefore be confined to results obtained by the second calculation method.

Included in Fig. 6 are results for higher fan-off $C_L$'s than that obtained at 12° incidence. If the stall could be prevented by means of circulation control, the maximum possible $C_L$ (see Appendix) for the

aspect/

aspect ratio-1 wing is seen to be 1.57 $\left(\frac{1}{\sqrt{C_L}} = 0.80\right)$ and the power requirement is then considerably greater than that required for hovering. The maximum thrust power requirement during transition is seen to take a minimum value when the manoeuvre is carried out at about 18° incidence, although the integrated total power requirements (or work done - which can be related to the area under the graph of Fig. 6) is least if fan-off wing supported flight is attained at an even higher $C_L$ (corresponding to the theoretical circulation appropriate to about 40°), and higher forward speeds are then obtained by reducing incidence in wing supported flight, rather than by completing transition at a lower incidence.

The influence of induced drag on this result can be seen from the graphs of Fig. 7 which show the composition of the D/L ratio for transition at incidences of 0°, 4°, 8° and 12°. Superimposed on the graph for 0° incidence is the induced drag component for wing supported flight. The induced drag included at other incidences is that associated with a constant induced drag coefficient equal to that achieved at the fan-off forward speed. Although the induced drag component is greater for transition carried out at the higher incidences, this is more than offset by the reduction in fan intake sink drag.

At medium incidences, the induced drag is so small a component of the total drag during transition that there is unlikely to be any substantial saving by increasing the aspect ratio of the wing. The effect of reducing the aspect ratio to 0.5 is shown in Figs. 8 and 9. The incidence for carrying out transition with least expenditure of work is now seen to be greatly reduced from the hypothetical 40° to an incidence only slightly greater than 12°.

The effect of increased fan area in relation to the induced drag was also examined. Increased fan area implies lower fan efflux velocity with a greatly increased momentum drag at an intermediate stage in transition. Hence the induced drag even for aspect ratio-1 is negligible in comparison with the fan momentum drag. Transition is therefore again best carried out at a very high incidence.

## 6. Conclusions

The experimental results, analysed in Ref. 1, of tests of a rectangular wing of aspect ratio 1 with a fan of area $A_F/A_W$ equal to 0.023 located at 0.354 chord suggested that peak power requirements in transition manoeuvres carried out at incidences $\leqslant 6°$ exceeded the hovering power requirements. The present calculations reveal that these peaks are due to the interference effects between jet and mainstream since they do not occur with the neglect of aerodynamic interference. The result that the power requirements for transition at 12° are less than the demands for transition at lower incidences is unaffected by the neglect of aerodynamic interference.

However,/

However, even with the neglect of jet/mainstream interactions, the calculations show that larger values of $A_F/A_W$ reduce the hovering power but result in the reappearance of large peak demands. These are to some extent alleviated by reduction in thrust engine loading, but appear to require provision for fan efflux deflection to eliminate them.

At incidences of 8° or less, induced drag forms only a small proportion of the drag, even for as low an aspect ratio as 1. If the aerodynamic stall could be avoided, the least power requirements for transition would be found to occur at as high an angle of incidence as 40°. It therefore appears to be desirable to carry out transition at an incidence as close to the stall as is considered feasible. For aspect ratio $\frac{1}{2}$ however, the optimum incidence would be about 12°.

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APPENDIX/

## APPENDIX

### Calculation Procedures

Different calculation procedures have been used in §§ 3-4 and in § 5. However, a common case was treated by each method and comparison of the results given in Figs. 2 and 6 show that although the two techniques have not led to identical answers, the same trends are exhibited by the two sets of curves.

The calculations have been concerned with the D/L ratio of the complete fan-wing combination, and with the output power ratio, $\xi$, whose definition is fully discussed in Ref. 1.

In § 3, the calculation of these parameters on the assumption that there is no interaction between the fan efflux and the main flow leans heavily on the experimentally observed results. The variation of the flow through the fan with change of forward speed has been taken to be the same as that actually measured (with interaction effects present), though the effective flow through the fan under static conditions has been derived from considerations of momentum applied to the measured fan lift. The effective velocity thus derived is appreciably less than the measured velocity (78%) because the figure obtained from the traverse readings was based on values obtained in the middle of each sector where the velocity was at a maximum and neglected the variations across each sector and also the reductions due to the boundary layers on the stator blades and duct and hub walls. Furthermore, the measured lift was probably reduced by the adverse ground effect due to the presence of the tunnel floor.

Under forward speed conditions the lift and drag increments due to fan operation have been derived from the momentum equation, assuming that the flow is taken into the fan with the forward speed and discharged in a direction normal to the wing chord with the effective efflux velocity. These increments have been added to the wing lift and drag measured with the fan inoperative, but the duct open. The fan power output has been taken to be proportional to the cube of the fan rotational speed, and its variation with the advance ratio was derived from the traverse measurements.

In the cases where the fan area has been taken to be different from that of the model tested, the power and the lift and drag increments due to fan operation have been taken to be proportional to fan area, whilst the wing lift and drag values to which the increments are added have been altered in such a way that the differences between the fan duct open values and the fan duct closed values (positive for drag, negative for lift) have remained proportional to the fan area.

In § 5, where the wing aspect ratio was also allowed to vary, a more fundamentally based procedure was used (still neglecting interactions). The derivation is as follows:-

The wing has aspect ratio $\Lambda$, span $2b$ and area $A_W$, so that $\Lambda = \dfrac{4b^2}{A_W}$. Hence

$$C_L \equiv \frac{L}{\frac{1}{2}\rho V_T^2 A_W} = \frac{L\Lambda}{2\rho V_T^2 b^2}. \qquad \ldots(1)$$

It is known that the formula for induced drag may be derived from momentum theory if it is assumed that the air flowing through a circle of diameter equal to wing span is affected by the wing and is deflected through an angle $\beta$. Hence, due to incidence $\alpha$ we have

$$L_\alpha = \rho\pi b^2 \ V_T^2 \sin\beta \qquad \ldots(2)$$

$$D_\alpha = \rho\pi b^2 \ V_T^2(1-\cos\beta) \qquad \ldots(3)$$

or

$$C_{L_\alpha} = \frac{\pi\Lambda}{2}\sin\beta \qquad \ldots(4)$$

and

$$C_{D_i} = \frac{\pi\Lambda}{2}(1-\cos\beta). \qquad \ldots(5)$$

On eliminating $\beta$, we obtain

$$C_{D_i} = \frac{\pi\Lambda}{2} - \sqrt{\left(\frac{\pi\Lambda}{2}\right)^2 - C_{L_\alpha}^2}. \qquad \ldots(6)$$

Note that this reduces to the more familiar result $C_{D_i} = C_{L_\alpha}^2/\pi\Lambda$ when $C_{D_i}$ is small compared with $C_{L_\alpha}$, and also that the maximum possible value of $C_{L_\alpha}$ occurs when $\beta = 90^\circ$, and that then $C_{L_\alpha} = C_{D_i}$.

The profile drag coefficient of the wing has been taken equal to 0.025, independent of incidence and fan area. This value is one half the measured minimum fan-off drag of the wing, as is appropriate.

When the wing is deriving part of its lift as circulation lift, and part from operation of the fan, which is assumed discharging air vertically downwards with velocity $V_F$, simple momentum theory which neglects all aerodynamic interactions shows that

$$L = C_{L_\alpha} \cdot \tfrac{1}{2}\rho V_T^2 A_W + \rho A_F V_F^2. \qquad \ldots(7)$$

Hence, using (1)

$\left(\dfrac{V_F}{V_T}\right)^2$ /

$$\left(\frac{V_F}{V_T}\right)^2 = \tfrac{1}{2}\left(\frac{A_W}{A_F}\right)\left(C_L - C_{L_\alpha}\right). \qquad \ldots(8)$$

We may therefore write

$$D = \text{Fan momentum drag} + \text{Wing induced drag} + \text{Wing profile drag}$$

$$\text{or} \quad \frac{D}{L} = \frac{\rho A_F V_F V_T}{L} + \frac{C_{D_1}}{C_L} + \frac{0.025}{C_L}$$

$$= \sqrt{2\frac{A_F}{A_W}\left(\frac{1}{C_L} - \frac{(C_L)_\alpha}{C_L^2}\right)} + \frac{1}{C_L}\left(\frac{\pi\Lambda}{2} - \sqrt{\left(\frac{\pi\Lambda}{2}\right)^2 - C_{L_\alpha}^2}\right) + \frac{0.025}{C_L} \qquad \ldots(9)$$

with the aid of equations (6) and (8).

The fan power output

$$P = \tfrac{1}{2}\rho A_F V_F (V_F^2 - V_T^2)$$

and the hovering fan power output

$$P_o = \tfrac{1}{2}\rho A_F V_{F_o}^3 \quad \text{where} \quad \rho A_F V_{F_o}^2 = L$$

$$= \tfrac{1}{2}L\sqrt{\frac{L}{\rho A_F}}$$

$$= \tfrac{1}{2}LV_T\sqrt{\tfrac{1}{2}C_L\frac{A_W}{A_F}}.$$

Hence, for zero acceleration, horizontal flight path and small angles of incidence, the output power ratio as defined in equation (8) of Ref. 1 is

$$\xi = \frac{\frac{1}{2}\rho A_F V_F (V_F^2 - V_T^2) + \frac{1}{2} D V_T + \sqrt{\frac{1}{4} D^2 V_T^2 + \frac{1}{2}\frac{D^3}{A_T \rho}}}{\frac{1}{2}\rho A_F V_{F_o}^3}$$

$$= \left(\frac{C_L - C_{L_\alpha}}{C_L}\right)^{\frac{3}{2}} \left(1 - \frac{2A_F}{A_W (C_L - C_{L_\alpha})}\right)$$

$$+ \left\{\frac{D}{L}\sqrt{\frac{2A_F}{A_W C_L}} + \frac{D}{L}\sqrt{\frac{2A_F}{A_W C_L} + \frac{2A_F}{A_T}\left(\frac{D}{L}\right)}\right\}$$

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Acknowledgement/

Acknowledgement

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References

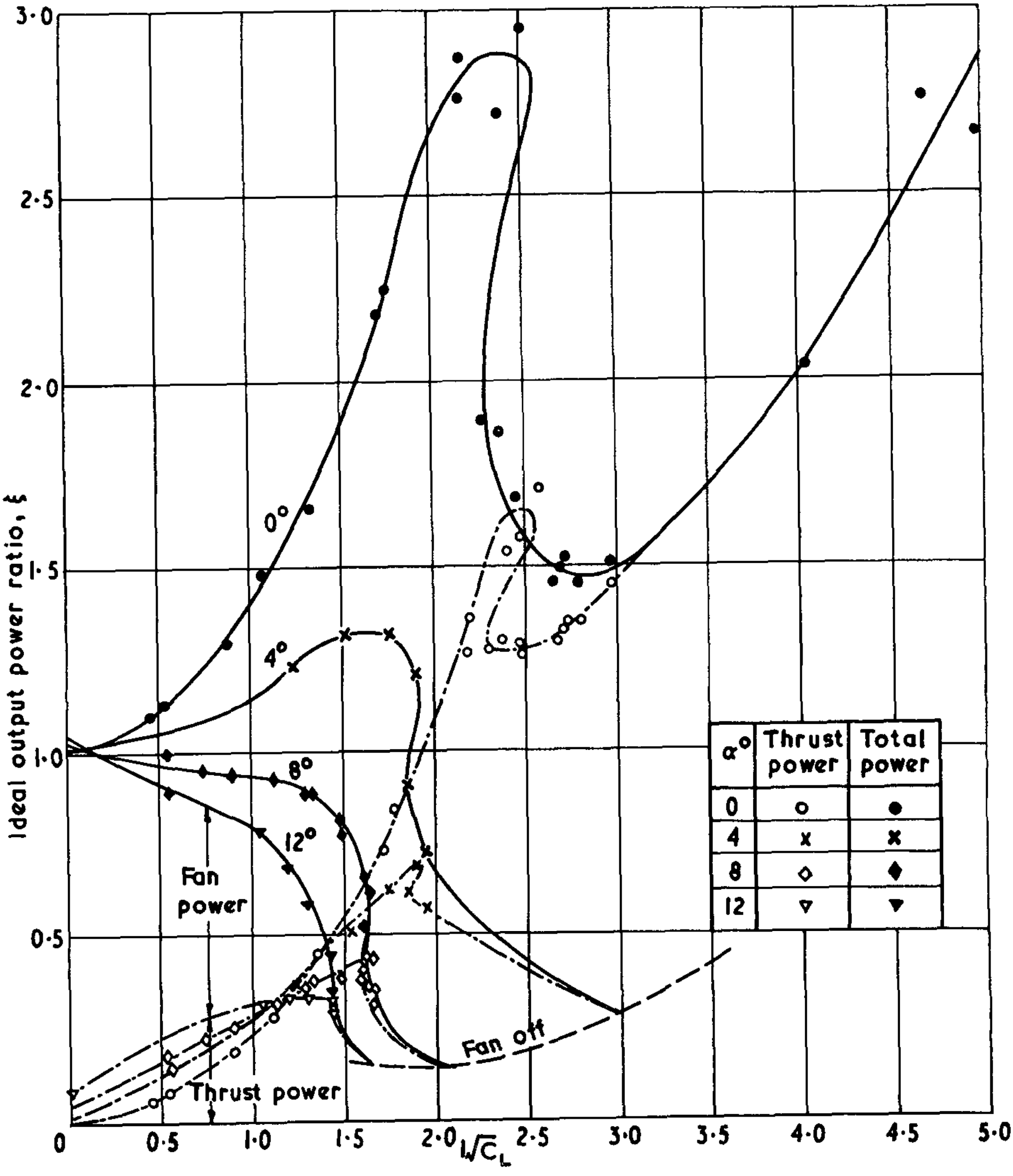

| No. | Author(s) | Title, etc. |
|---|---|---|
| 1 | N. Gregory | On the representation of fan-wing characteristics in a form suitable for the analysis of transition motions, with results of tests of an aspect-ratio-1 wing with fan at 0.354 chord. A.R.C. C.P. No.552, August 1959. |
| 2 | N. Gregory, W. G. Raymer and E. M. Love | Wind-tunnel tests of wings fitted with single lifting fans. Report in preparation. |

## ADDENDA

It is desirable to emphasize the very approximate nature of the calculations which were undertaken in §5 in order to draw attention to the economy of carrying out transition at a high value of $C_L$ and to the relative unimportance of induced drag compared with fan momentum drag, even for the present wing of aspect ratio only 1 and low fan area. It is not thought that these conclusions are greatly affected by the crudity of the calculations, but the reader should be reminded that the low aspect ratio results in a very low lift curve slope (not quite as low as accurate theory predicts, as the experimental results on which the calculations are based have not been corrected for wind-tunnel interference, which has a favourable effect). The results therefore appear rather less startling stated in terms of $C_L$ rather than of incidence. For the aspect-ratio 1 wing, for which the ultimate possible $C_L$ is only 1·57, the incidence for transition with the minimum value of maximum thrust demand is that at which the fan-off $C_L$ is 0·52, and the higher incidence for minimum integrated power demand is that corresponding to a $C_L$ of 1·0 if this could be attained without stalling. Nevertheless, these conditions demand such high angles of incidence that the neglect of the inclination of the fan and thrust engine axes is not justified: their inclusion would result in some detail modification of the results.

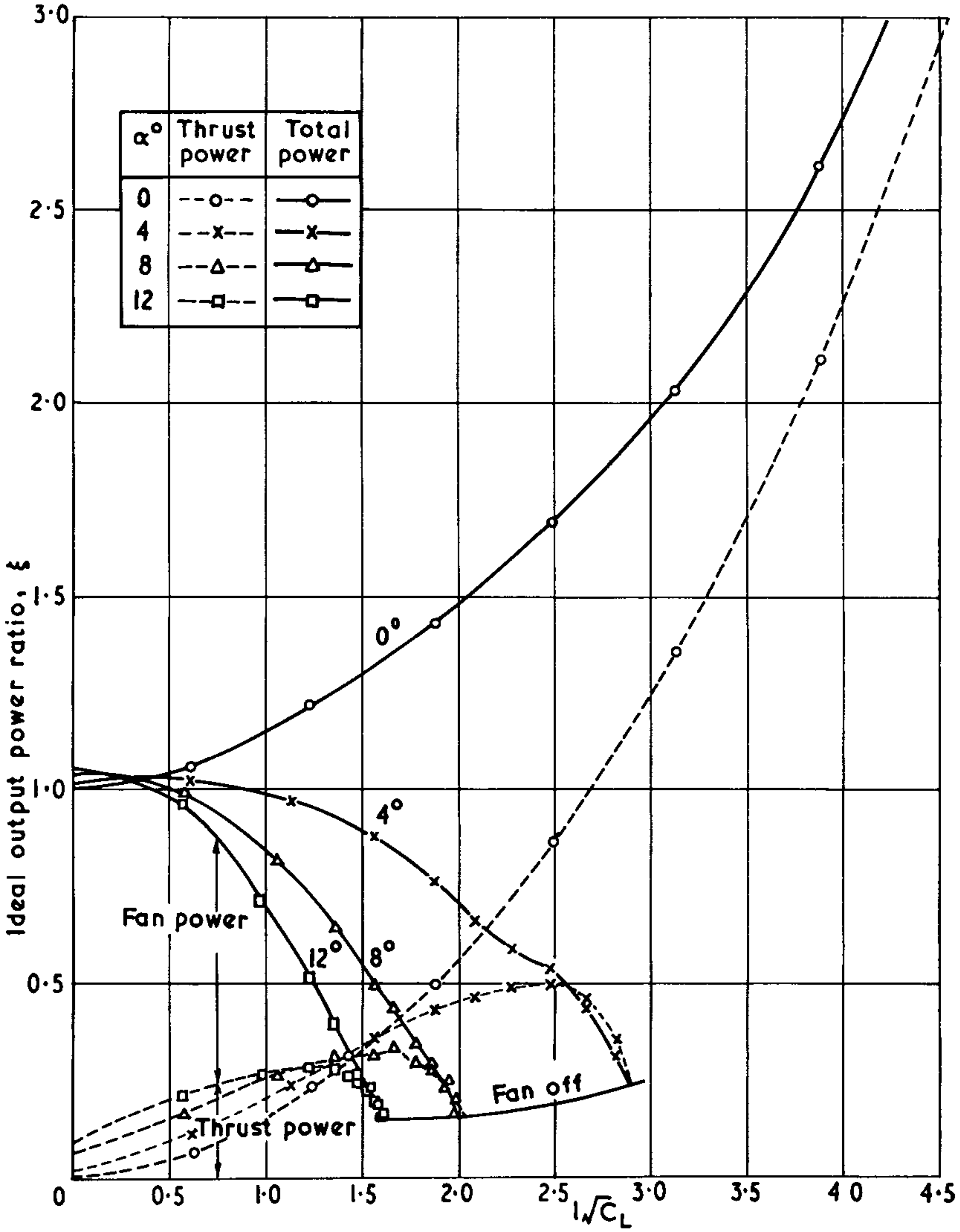
The further argument concerning the reduction of aspect ratio from 1 to $\frac{1}{2}$ is also very approximate as no account has been taken of the considerable theoretical reduction in fan-off lift curve slope, which would be almost halved compared with the aspect ratio 1 case. The angles attached to the curves of Figs.8 and 9 are therefore incorrect. The conclusion is that transition is carried out with least expenditure of work at a $C_L$ of about 0·35 (compared with the maximum theoretically possible of about 0·78) which occurs (in the absence of the stall) at an incidence of about 27° instead of 12° as stated. This result would also be modified by including the effect of fan and thrust engine tilting with the wing.

FIG. 1




Variation of ideal output power ratio with forward speed parameter and incidence for aspect ratio -1 wing with fan at 0·354 chord. $A_F/A_W = A_T/A_W = 0\cdot023$

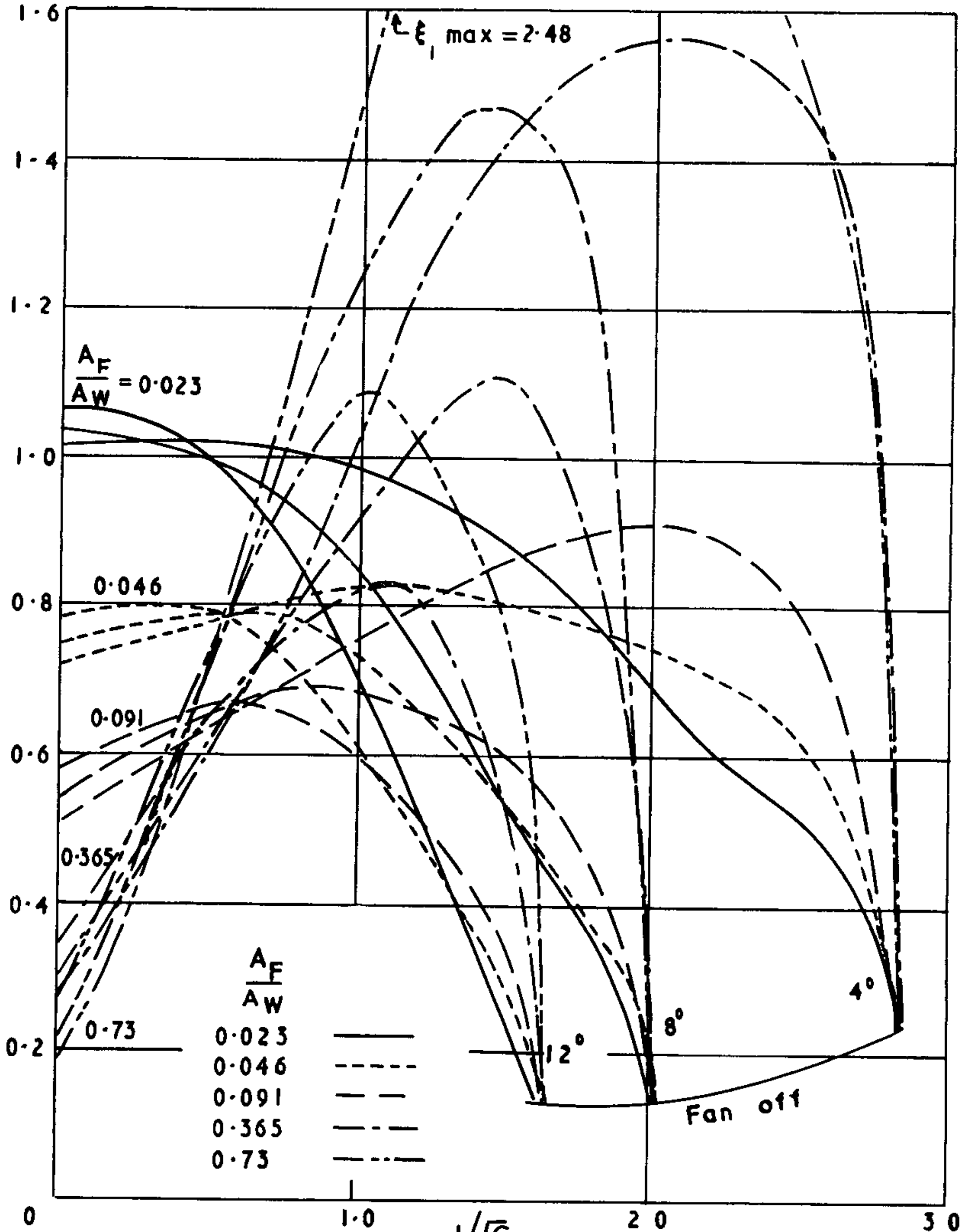
FIG. 2




Variation of ideal output power ratio with forward speed parameter and incidence, calculated for aspect ratio -1 wing on the assumption of no aerodynamic interference between efflux and mainstream.

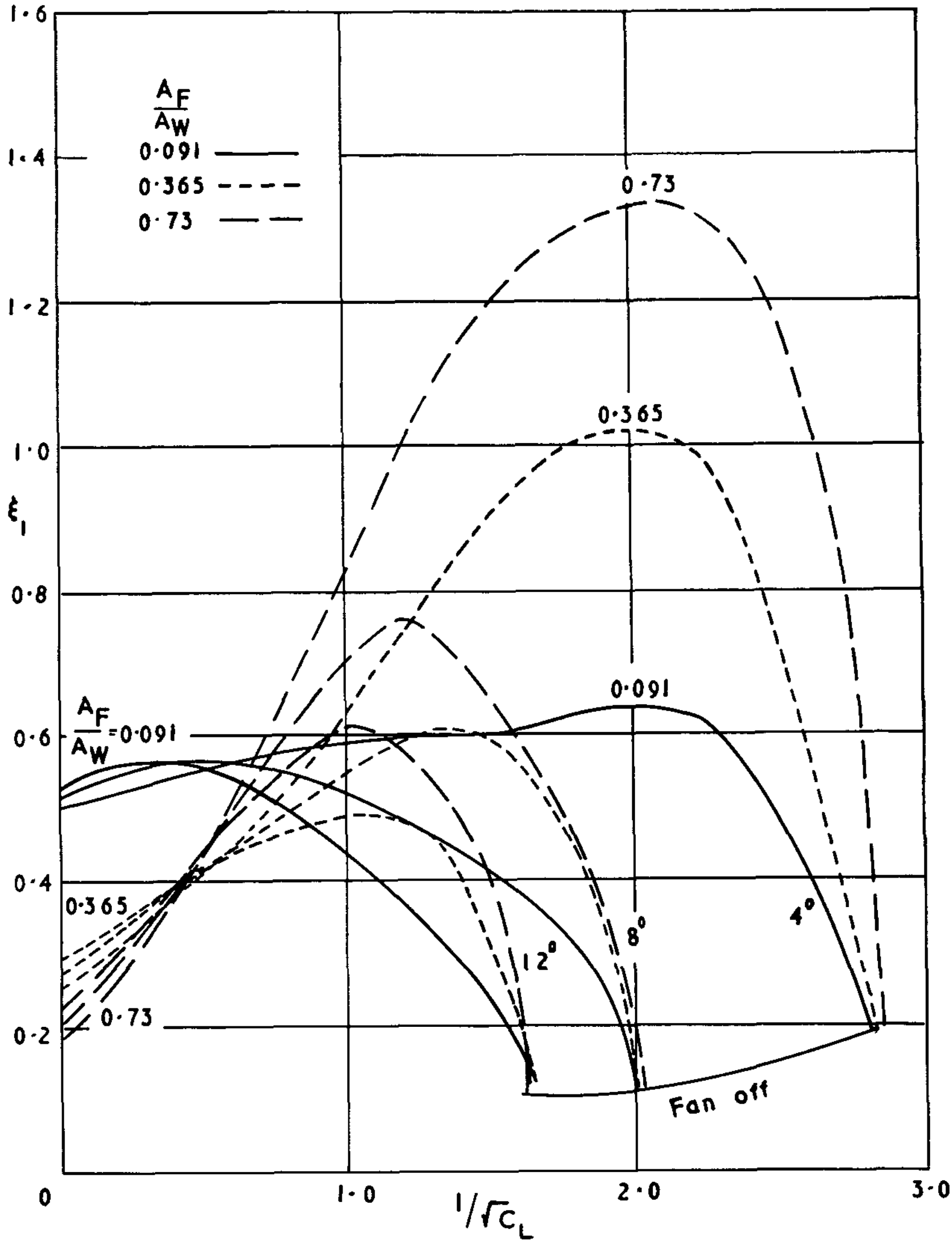
$A_F / A_W = A_T / A_W = 0{\cdot}023$

FIG. 3



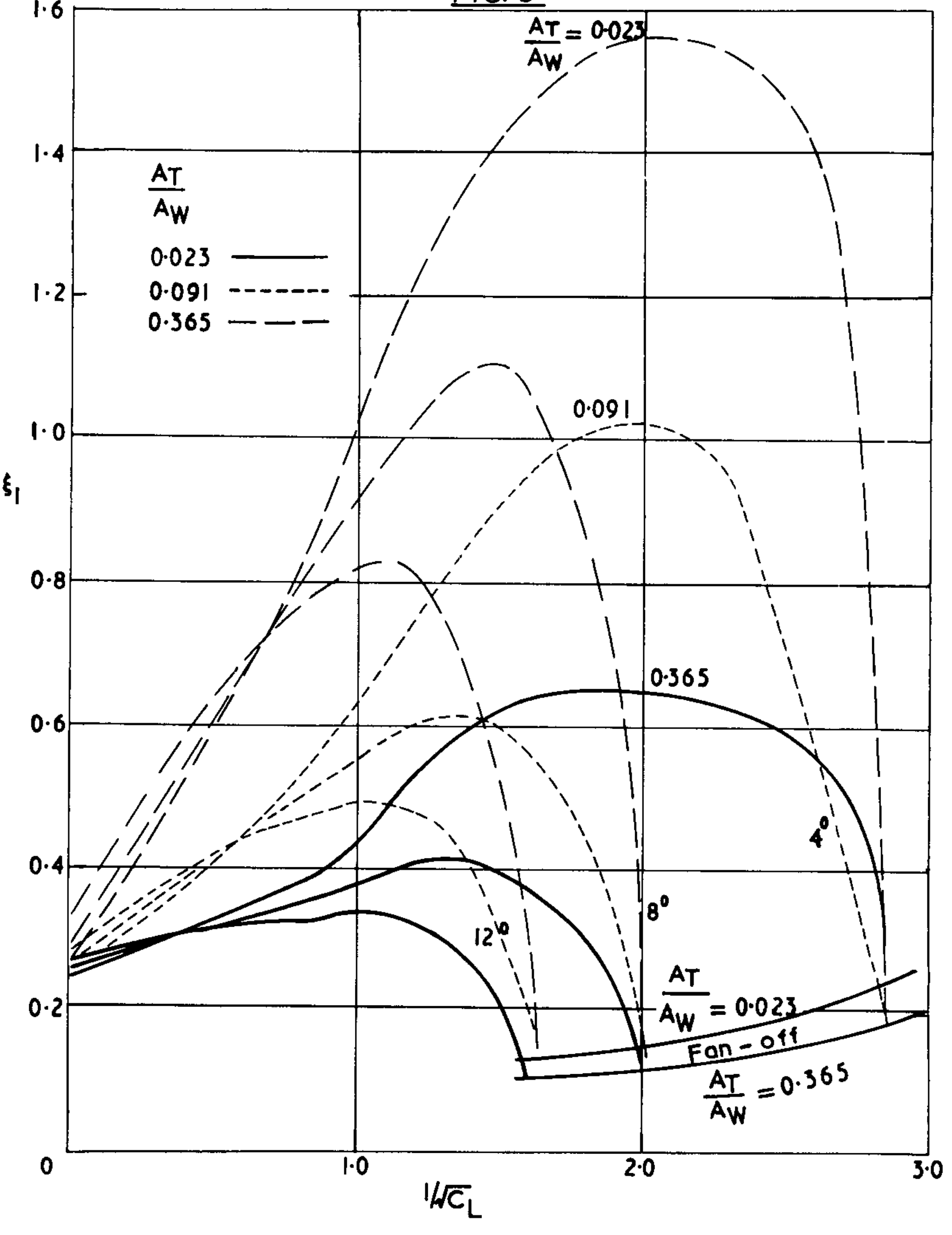

Variation with forward speed parameter of the ratio of the ideal output power to the 0° incidence hovering power for $A_F/A_W = 0{\cdot}023$.
$A_T/A_W = 0{\cdot}023$, $A_F/A_W$ varied.

FIG 4




Variation with forward speed parameter of the ratio of the ideal output power to the 0° incidence hovering power for $A_F/A_W = 0.023$ $A_T/A_W = 0.091$, $A_F/A_W$ varied.

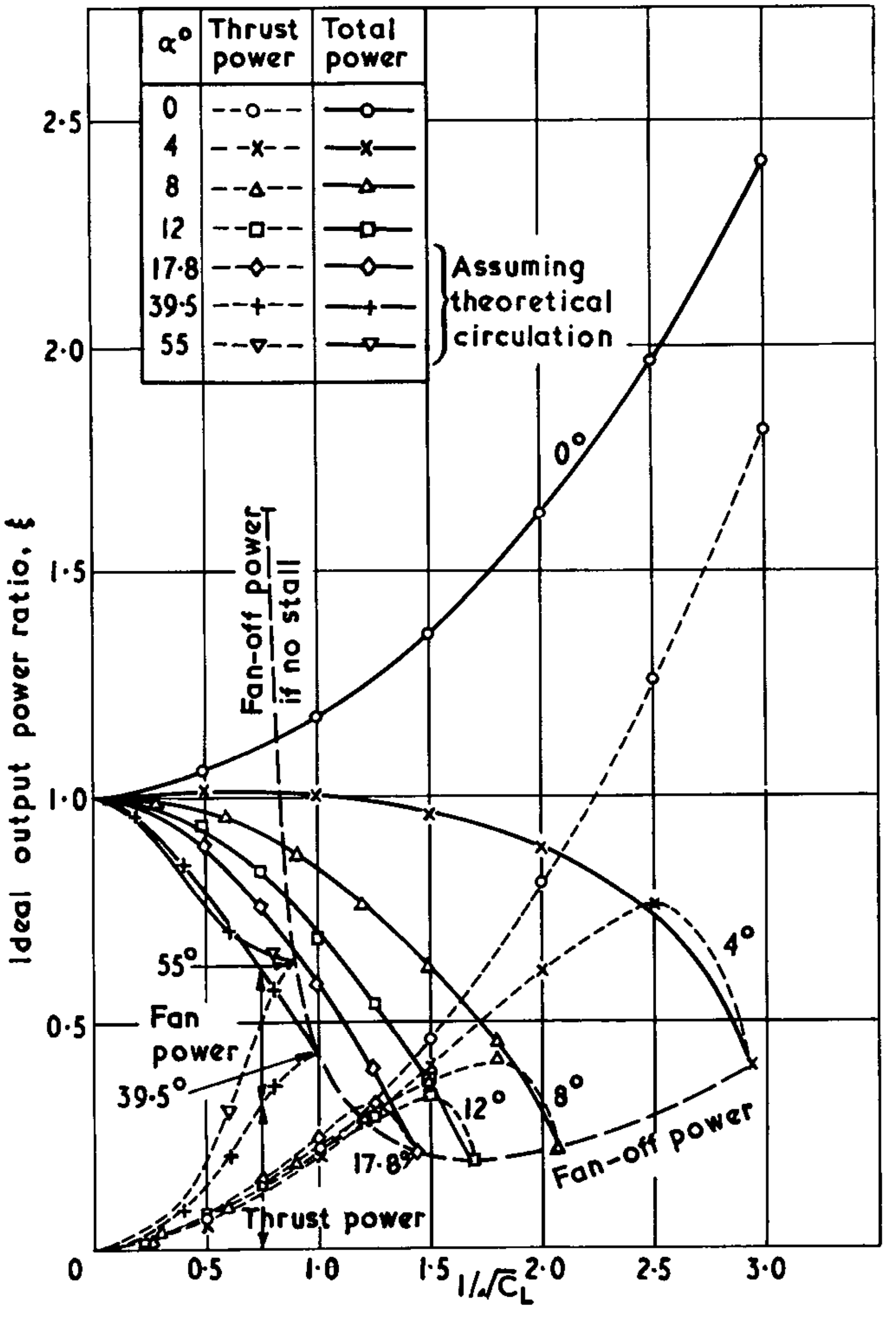
FIG. 5




Variation with forward speed parameter of the ratio of the ideal output power to the 0° incidence hovering power for $A_F/A_W = 0{\cdot}023$

$A_F/A_W = 0{\cdot}365$, $A_T/A_W$ varied

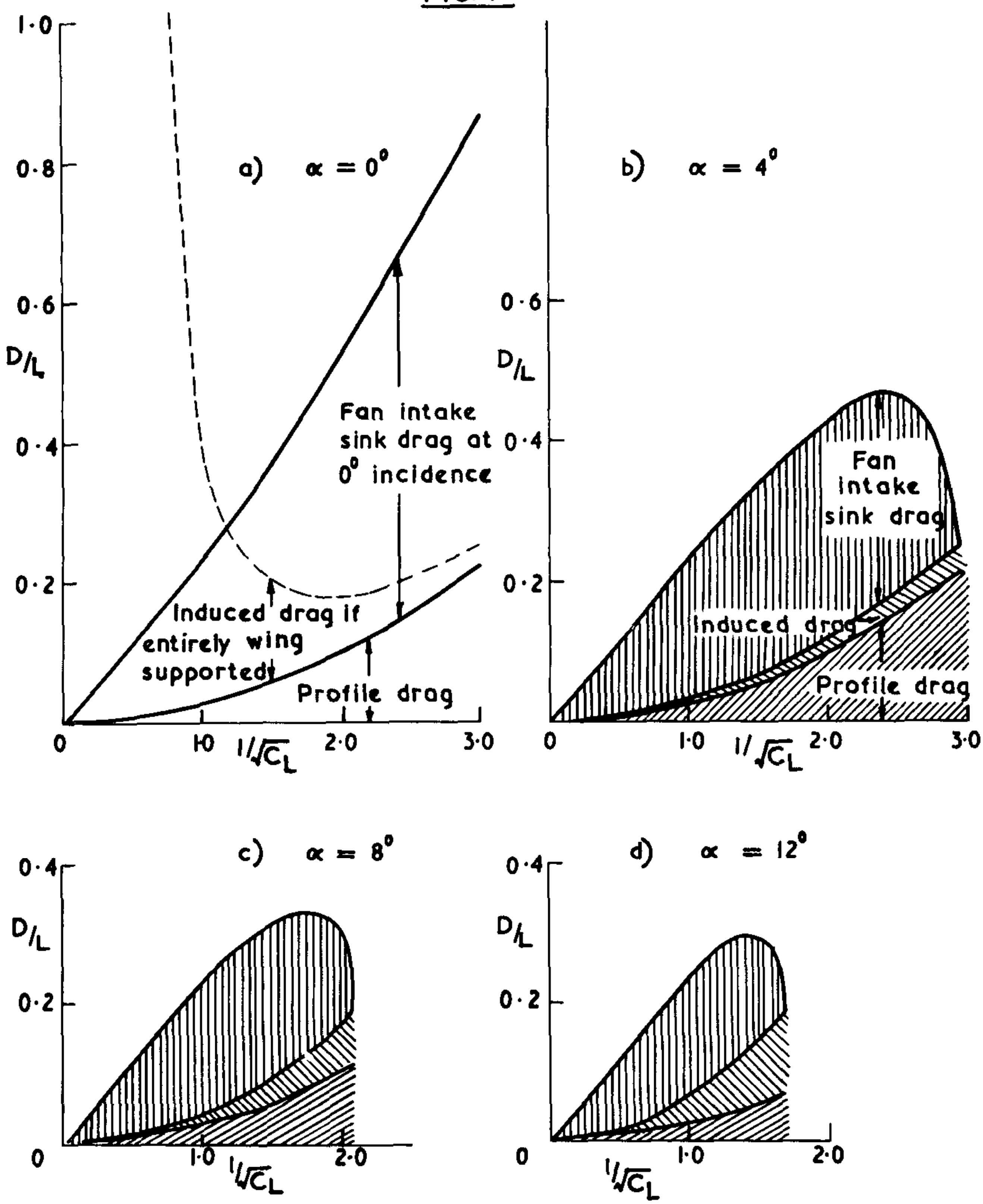
FIG. 6




Calculated variation of ideal output power ratio with forward speed parameter and incidence for aspect ratio -1 wing. Second technique of Appendix used, assuming no aerodynamic interference.

$A_F/A_W = A_T/A_W = 0{\cdot}023$

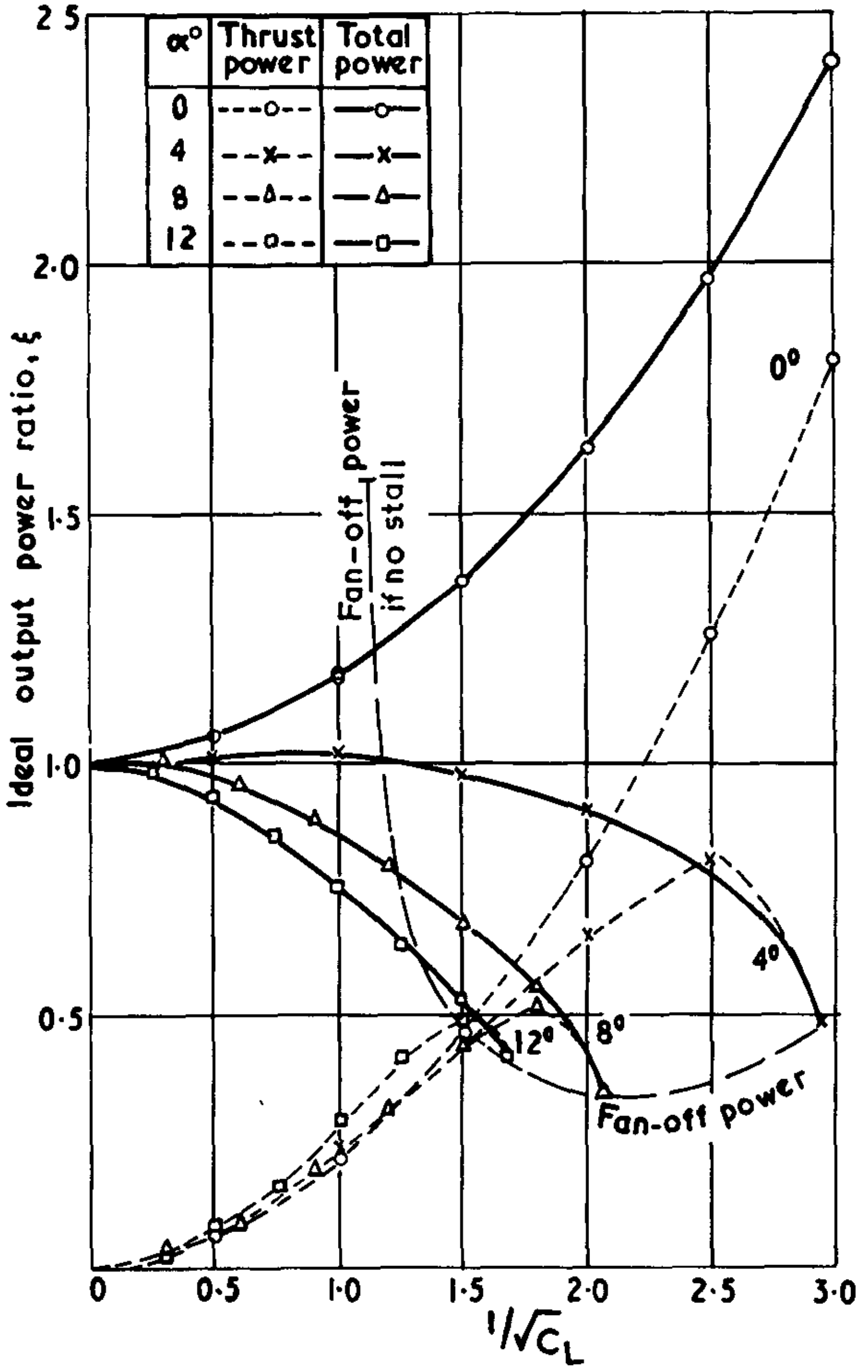
FIG. 7




Variation of the calculated value of $D/L$ with forward speed parameter for various incidences. No aerodynamic interaction.

$A_F/A_W = A_T/A_W = 0{\cdot}023$ Aspect ratio 1.

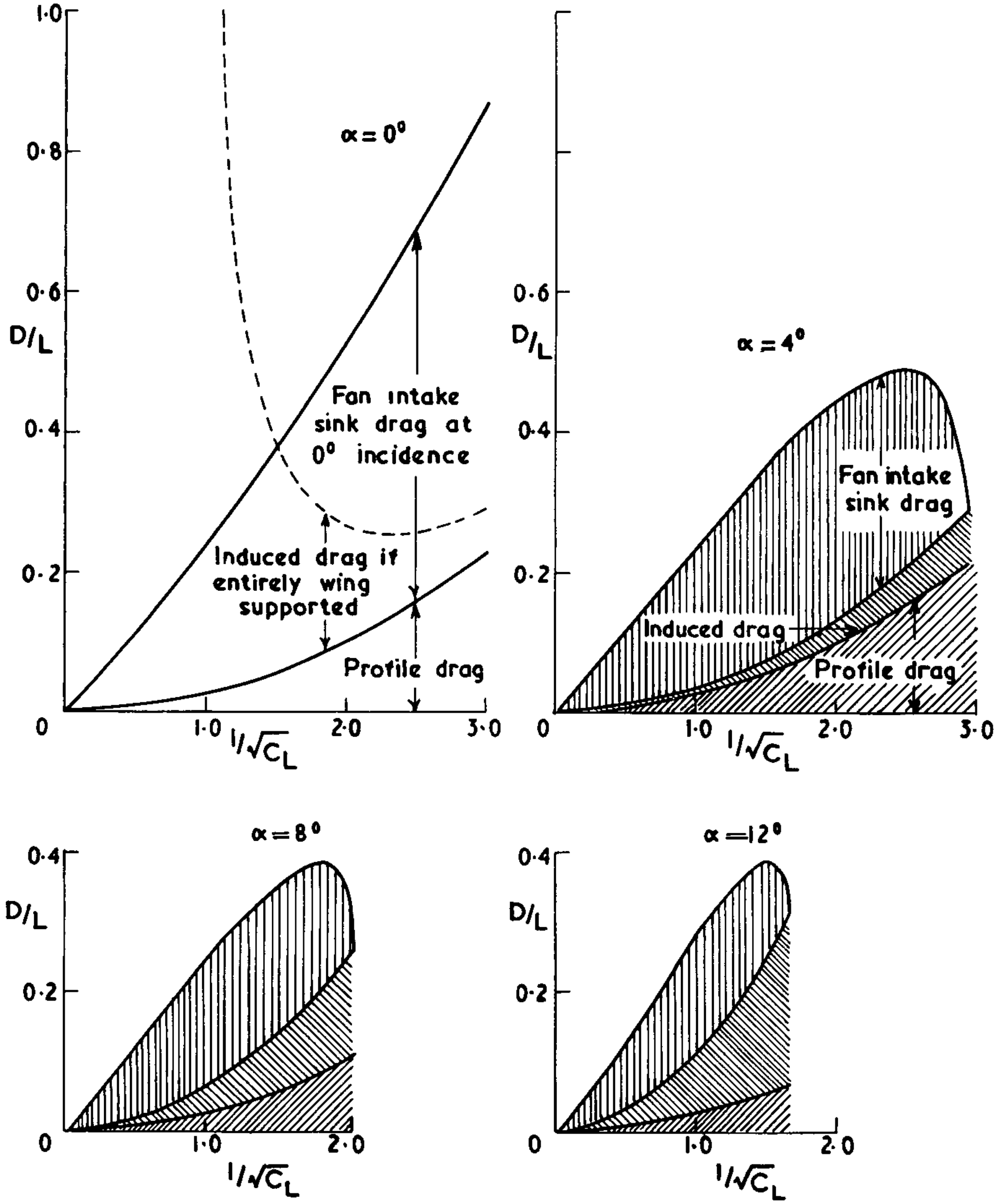
FIG. 8.




Calculated variation of ideal output power ratio with forward speed parameter and incidence for aspect ratio – 0·5 wing.

$A_F / A_W = A_T / A_W = 0{\cdot}023$

FIG 9




Variation of the calculated value of $D/L$ with forward speed parameter for various incidences. No aerodynamic interaction.

$A_F / A_W = A_T / A_W = 0{\cdot}023$ Aspect ratio 0·5.

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