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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

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SUMMARY

A method is 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 procedure takes into account the effect on power requirements of variation of thrust engine loading in relation to that of the fan.

As an example, results are displayed of tests of a rectangular wing of aspect ratio 1 with fan located at 0.354 chord. It appears that transition from hovering to wing-supported flight is more economically made at the highest angle of incidence of the tests, 12°. Further research is required to ascertain how much this result is affected by variations in wing and fan geometry. The effects of an 0.3g horizontal acceleration and of deflection of fan efflux by a flat plate cascade on the power requirements are also considered.

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1. Notation

ρ density of air, slugs/ cu ft

α incidence

Γ angle of flight path to horizontal

s distance

d fan diameter

c wing chord

x chordwise distance from leading edge

A_W wing area

A_F fan annulus area

V_T speed of translation (forward speed) or tunnel wind speed

V_F mean velocity of flow through fan

n fan rotational speed revs/sec

μ/

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μ	$= V_T/\pi nd$, ratio of forward speed to fan blade tip speed
$\frac{1}{\sqrt{C_L}}$	forward-speed parameter: see C_L
$\frac{1}{\sqrt{C_T}}$	fan-speed parameter: see C_T
L	lift
ΔL	lift increment due to operation of fan
D	drag
T_e	thrust (of thrust engine)
W	weight
NW	accelerating force
M	moment
P	fan power
ΔH	pressure rise across fan
C_T	fan thrust coefficient $= L/\frac{1}{2}\rho A_F(\pi nd)^2$
C_L	lift coefficient $= L/\frac{1}{2}\rho A_W V_T^2$
C_D	drag coefficient $= D/\frac{1}{2}\rho A_W V_T^2$
C_m	moment coefficient $= M/\frac{1}{2}\rho A_W c V_T^2$
K_p	fan power coefficient $= P/\frac{1}{2}\rho A_F(\pi nd)^3$
ζ	fan static thrust factor of merit $= C_T/(2K_p)^{\frac{2}{3}}$ when hovering
ξ	output power ratio, see equation (8)
R_c	chord Reynolds number $V_T\, c/\nu$
	suffix o refers to hovering conditions

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2. Introduction

The results of preliminary wind tunnel tests of fan wings[1,2] have hitherto been presented in a form intended to exemplify the aerodynamics of the interaction between the fan efflux and the forward motion. It has been shown, for example, that the flow pattern is determined by the incidence and the ratio of forward speed to fan efflux velocity, V_T/V_F, and it has appeared that for forward locations of the fan, the lift increment due to the fan has initially decreased with increase of forward speed from rest at constant incidence, thus suggesting that an increase in fan revolutions, and presumably in power also, would be required to keep an aircraft airborne. The lift increment due to the fan has also been found not to be greatly affected by wing incidence.

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For performance analysis, however, consideration of lift increments alone may be somewhat misleading. It is necessary to consider the aircraft as a whole since at some positive angle of incidence, the increase in "circulation" lift with forward speed will balance the fall-off in fan-lift increment and increased fan resolutions and power input may not then be required. A new form of representation of the results of wind-tunnel tests of fan wings is suggested below, and should prove suitable for the analysis of transition motions. Results of some recent wind-tunnel tests are given in the new form, which clearly demonstrate the effects of incidence, acceleration and of fan efflux deflection on the power requirements in transition.

3. The Framework for Analysis

A simple analysis of transition motions for a V.T.O.L. system with a tilting thrust engine has recently been given by Gates and Griggs[3]. In this it was possible to neglect the interference between the thrust engine and the characteristics of the aircraft without it. From what has already been said, it is clear that this is no longer true for the fan wing. Although due allowance for the interference can be made by the use of the experimentally determined characteristics of a fan wing, this will preclude any simple analytical solutions of the transition motions. However, the force diagram to be solved is in some respects simpler than that considered in Ref.3. Using the same notation as far as is appropriate, the forces and force polygons for straight-line accelerations at positive incidence are as shown in Fig.1. The fan wing itself is subject to lift, L, and drag, D, both of which at any given incidence and forward speed are altered by the pilot's control of the fan rotational speed. In addition the aircraft is assumed to have an engine producing thrust, T_e, in the direction of the (zero lift) chordline.

Resolving normal and parallel to the direction of motion gives the following relations

$$L = W \cos \Gamma - T_e \sin \alpha \qquad \ldots (1)$$

$$NW = T_e \cos \alpha - W \sin \Gamma - D \qquad \ldots (2)$$

where Ng is the acceleration of the aircraft.

The details of the motion are determined, as in Ref.3, by integration of the equations

$$\frac{1}{g}\frac{dV_T}{dt} = \frac{1}{2g}\frac{dV_T^2}{ds} = N. \qquad \ldots (3)$$

It is not the intention to investigate here the economics of various transition motions, but merely to point out that if the transition consists essentially of a slow vertical rise in a normal attitude to some suitable height, followed by acceleration along a straight path making a suitable small angle Γ to the horizontal with the wing operating at an angle of incidence α, then equations (1) and (2) allow the details of the latter motion to be calculated. For provided the engine thrust T_e is known, equation (1) determines the required lift, L, and equation (2) shows that the resulting acceleration can also be determined as the value of the drag D is now known, being fixed by the combination of forward speed, incidence and fan rotational speed that is necessary to produce the required lift, L.

Lift and drag axes are thus seen to be convenient axes along which to resolve the forces acting on a fan wing, especially in relation to the accelerated portion of the flight since acceleration along a straight flight path does not influence the lift required to be developed by the aircraft. This consideration would not have been true had axes normal and parallel to

the/

the chordline been used: such axes would, however, have been more convenient to describe the hovering condition where normal force and tangential force are not affected by incidence, and also to describe the air loads due to the initial vertical motion if these have to be taken into account. The wing is then operating at angles of incidence close to $\pm 90^\circ$ and the use of normal and tangential axes avoids an effective interchange between the magnitude of the two components. However, the second stage of transition is undoubtedly the one of greatest interest, so lift and drag axes have been chosen.

4. Non-Dimensional Parameters for representing Fan-Wing Characteristics

Dimensional analysis applied to a conventional low-speed wing shows that the dependent forces (L, D, M) can be reduced to dimensionless groups (C_L, C_D, C_m) which are functions of only two variables, incidence α, and Reynolds number R_C. Model and full-scale tests further show that the coefficients are but slowly moving functions of Reynolds number so that for many purposes, variations in this parameter may be neglected.

It has already been indicated that for the case of a fan wing, the flow pattern is determined also by the ratio V_T/V_F, where V_F is the mean velocity of the flow through the fan duct. Thus it would be possible to represent results on fan wings in the form that C_L, C_D, C_m were functions of α, V_T/V_F, and to a lesser extent, Reynolds number. This is quite unsuitable since the coefficients all become infinite when V_T is zero and therefore convey little information about hovering conditions. Also it would be difficult conveniently to show the dependence of the values of the coefficients at constant incidence upon the parameter V_T/V_F since the values of this parameter (or its reciprocal) extend from 0 to ∞.

The difficulty is resolved if lift is no longer regarded as a dependent variable as is implicit in the conventional viewpoint when C_L is regarded as a function of incidence, α. Indeed, equation (1) indicates that to support a given aircraft in the air a definite value of lift is required, and that forward speed, incidence and fan speed must be adjusted to suit. Fan efflux velocity V_F is now regarded as a derived variable since it is a function not only of the fan rotational speed but also to some extent of the forward speed, though the influence of this may be slight. For the purpose of analysis, therefore, the fan rotational speed has been used as primary variable rather than V_F. The rotational speed is conveniently measured in terms of the blade tip speed πnd where n is in revs/sec.

The principal dependent variable will therefore be the fan rotational speed which is required to produce a given lift at given incidence and forward speed. The drag and pitching moment are thence also determined and analysis shows that these dependent variables are suitably represented by the following dimensionless parameters:-

$$\text{fan-speed parameter,} \quad \pi nd \sqrt{\frac{\frac{1}{2}\rho A_F}{L}}$$

$$\text{drag/lift ratio,} \quad \frac{D}{L} \quad \text{and}$$

chordwise position, x/c, of the centre of pressure, which when measured from the axis about which the moments are taken, is equal to M/Lc.

These/

These parameters are functions of

incidence, α and

forward-speed parameter, $V_T \sqrt{\dfrac{\frac{1}{2}\rho A_W}{L}}$.

Different reference areas have been taken for the fan-speed parameter and the forward-speed parameter so that the squares of the reciprocals of these parameters are the fan thrust coefficient and wing lift coefficient whose behaviours under hovering and fan-off conditions respectively should be already known. For these reasons, the fan speed parameter is written $1/\sqrt{C_T}$ and the forward speed parameter $1/\sqrt{C_L}$.

The remaining characteristic of a fan wing not so far discussed is that of the power required to operate it. This power is expended in two ways, by the engine rotating the fan, and by the thrust engine in producing thrust.

The total power can conveniently be considered in terms of a non-dimensional ratio which may be defined by the following:-

> Power input to the fan plus power input to the thrust engine, divided by the power put into the fan when hovering at zero incidence and supporting the same weight of aircraft.

This implies that the value of the ratio will be 1 when hovering at zero incidence, but not necessarily 1 when hovering at other than zero incidence, the aircraft then being supported by a combination of lift and thrust.

In the tests described below, it was not possible to measure the power input to the fan, whose efficiency was not known. It is therefore convenient to assume that the fan and thrust producing mechanisms are of equal intrinsic efficiency and to consider an output power ratio ξ which is defined by:-

> 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.

An expression for the output power ratio in terms of experimentally observed quantities is derived as follows. The fan output power P is equal to $A_F \, \Delta H \, V_F$ where ΔH and V_F can be determined from pitot-static traverses across the fan duct. The power output of the fan can be expressed in terms of a power coefficient in a conventional fashion, as

$$K_P = \frac{P}{\frac{1}{2}\rho A_F[\pi n d]^3} \quad . \qquad \ldots (4)$$

Since such a power coefficient is, apart from scale effect, dependent upon the pressure ratio across the fan and the inflow distribution, it will principally be determined by the value of μ, i.e., the ratio of forward speed to fan blade tip speed $V_T/\pi n d$.

The thrust required (T_e) and the weight of aircraft supported (W) are determined in terms of the lift and drag measured in a wind-tunnel test by solving equations (1) and (2) and obtaining

T_e/

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*Also relative to the aircraft. This includes the wasted work as well as the useful work $T_e V_T$ performed in moving the aircraft.

$$T_e = \frac{D \cos \Gamma + NL + L \sin \Gamma}{\cos (\Gamma + \alpha) - N \sin \alpha} \quad \ldots (5)$$

and

$$W = \frac{L \cos \alpha + D \sin \alpha}{\cos (\Gamma + \alpha) - N \sin \alpha} . \quad \ldots (6)$$

Simple actuator disc theory[4] applied to the thrust engine shows that the rate of doing work on the fluid by the thrust of an ideal actuator is $T_e(V_T+v)$ where v is the added velocity at the actuator disc, and where T_e, the thrust, is given by momentum considerations as

$$T_e = 2 A_T \rho (V_T + v) v \quad \ldots (7)$$

where A_T is the area of the actuator. Eliminating v, the rate of doing work on the fluid by the actuator is $\frac{1}{2}T_e V_T + \sqrt{\frac{1}{4} T_e^2 V_T^2 + \frac{1}{2} \frac{T_e^3}{A_T \rho}}$, the second term in the numerator of the output power ratio.

The denominator of the output power ratio is the power required when hovering to support the same weight of aircraft as is supported at the forward speed concerned. In wind tunnel tests carried out at constant fan rotational speed, the lift varies with forward speed and so does the weight of aircraft supported: hence the power measured when hovering has to be scaled to the same supported weight as is measured at forward speed. This latter weight is given by equation (6). On the other hand, the weight of aircraft that could be supported by the hovering power P_o, if the aircraft were rotated to zero incidence to the horizontal, can be determined from wind tunnel tests carried out at incidence α to the horizontal since it is clearly equal to the force resolved normal to the chord when at incidence α, i.e., to $L_o \cos \alpha + D_o \sin \alpha$ where P_o, L_o and D_o are the values measured at incidence α under hovering conditions. Since hovering power is proportional to the $3/2^{th}$ power of the force produced (as is shown also by the expression for the actuator power which follows equation (7)) the denominator of the output power ratio is given by

$$P_o \left[\frac{L \cos\alpha + D \sin\alpha}{(L_o \cos\alpha + D_o \sin\alpha)(\cos (\Gamma+\alpha) - N \sin\alpha)} \right]^{\frac{3}{2}}$$

Thus the complete expression for output power ratio is

$$\xi = \frac{P + \left[\frac{1}{2}T_e V_T + \sqrt{\frac{1}{4} T_e^2 V_T^2 + \frac{1}{2} \frac{T_e^3}{A_T \rho}} \right]}{P_o \left[\frac{L \cos\alpha + D \sin\alpha}{(L_o \cos\alpha + D_o \sin\alpha)(\cos (\Gamma+\alpha) - N \sin\alpha)} \right]^{\frac{3}{2}}} \quad \ldots (8)$$

where T_e is given by equations (5) and P is given by equation (4) and the suffix o refers to hovering conditions at incidence α.

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5. Results of Tests of an Aspect-Ratio 1 Fan Wing Displayed in the New Form

5.1 Force measurements on the plain wing

Recent N.P.L. wind tunnel tests of a symmetrical 15% thick rectangular wing of aspect ratio 1 with a fan whose axis is located at 0.354 are presented here in the new form: the tests concerned have not yet been written up elsewhere in detail. The relation between fan-speed parameter and forward-speed parameter at various angles of incidence is shown in Fig. 2, whilst Fig. 3 is an extra graph which plots the relationships between the squares of the two speed parameters. The dependence of drag/lift ratio and centre of pressure position on incidence and forward-speed parameter are shown in Figs. 4 and 5, whilst Figs. 6 and 7 deal with power requirements.

In Figs. 2 and 3, points relating to different incidences at fixed values of the ratio, μ, of forward speed to fan blade tip speed lie on rays through the origin. On the other graphs, curves of constant values of μ have been obtained by cross-plotting from Fig. 2, and are given except where their inclusion would lead to confusion.

In Figs. 2 and 3 the rise in the value of the ordinate of the 0° curve as the forward speed increases from zero corresponds to the typical initial decrease in $\Delta L/\rho A_F V_F^2$ with increase of V_T/V_F previously reported[2], whilst the subsequent fall in the value of the ordinate corresponds to the subsequent increase in $\Delta L/\rho A_F V_F^2$. Fig. 3 is particularly interesting. With these ordinates, if there were no interaction between efflux and mainstream (so that the lift on the wing was equal to the sum of the aerodynamic lift due to incidence and wind speed, together with the fan lift due to operation of the fan at the same rotational speed under static conditions), then the characteristic would be the straight line joining the two intercepts. Since experiment has shown that (in the absence of guide vanes) the mean velocity of flow through the fan is but little affected by forward speed (an increase of 7% as μ increases from 0 to 0.35), the curves plotted may be sensibly compared with straight lines joining the intercepts. At low forward speeds where the curves are convex upwards, the effects of interaction are adverse; at higher speeds where the curves are concave, the interaction effects become favourable. There must be one or more limiting curves to the series, corresponding to the stall, and flight is not possible in the region between this envelope and the origin. As this region is somewhat minimised by Fig. 3 and undue emphasis given to the high-speed region of the graph, the linear speed scales of Fig. 2 are probably to be preferred: on these scales, however, interaction-free curves become quarter-ellipse and the interaction effects are not so obvious from inspection.

In Fig. 2, the value of the ordinate obtained under hovering conditions is not independent of incidence but is clearly equal to a constant multiplied by $(\sec \alpha)^{\frac{1}{2}}$. Even at 12° incidence, the difference between $(\sec \alpha)^{\frac{1}{2}}$ and unity is only 1% and is quite undetectable in the graph, as also are the corresponding differences in Fig. 3.

If a slow transition motion is assumed to take place along a horizontal flight path so that the lift required is substantially equivalent to the aircraft weight ($N = 0$, $\Gamma = 0$ and α small in equation (6)), Figs. 2 and 3 indicate how increased fan revolutions are at first required at zero incidence, though at or above 4° incidence, the increase in circulation lift exceeds the fall off in lift increment so that the fan revolutions required decrease continuously from the start. This only shows what fan rotational speed is required to maintain a constant lift and must not be confused with the power requirements, discussed below for more general conditions, which are needed to support a given weight.

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The variation of drag/lift ratio with forward speed parameter, is shown in Fig.4, and the hovering values are equal to tan α. The drag/lift ratio rises rapidly with increase of forward speed, the drag being of the same order of magnitude as the intake sink drag. As the speed rises, the fan may be slowed down and a maximum value of the drag is found: as also indicated by the previous graph, it is advantageous to perform the transition at a high positive angle of incidence where the maximum value is least.

The variation of centre of pressure of the overall lifting force with incidence and forward speed shown in Fig.5 gives a measure of the trimming moment which must be supplied by tailplane or air-jets.

5.2 Fan output power measurements

The apparatus of these particular tests did not allow the power input to the fan to be measured. However, a number of total head and velocity traverses were made in the fan efflux immediately downstream of the fan. From these it was possible to estimate the mean flow velocity through the fan, whilst the pressure rise across the fan was taken to be given by the difference between the downstream total head in the efflux and the undisturbed total head in the tunnel far upstream. Thus it was possible to estimate an ideal fan power output which is the rate of work done by the fan on the flow through the fan on the assumption that there are no losses upstream of the fan or in turning the corner at entry. If such losses were in fact present, then the fan power output must have been greater than that estimated which therefore represents a minimum or ideal value for the particular size of fan. The variation of the ideal output power coefficient with μ is shown in Fig.6. It will be seen that under hovering conditions this coefficient is reasonably independent of rotational speed, and that at values of μ up to 0.3 at any rate, is also independent of wing incidence*. At very high values of μ the latter feature would no longer be true since the pressure difference between the fan intake and exit (fan off) varies with incidence and the flow through the fan at low fan rotational speeds would be affected by incidence. However, as can be seen from Figs.2 and 3 the fan is operated in practice at high values of μ only at greatly reduced rotational speeds, and any errors in estimation of power are then of little significance. Although Fig.6 shows the ideal power output of the fan decreasing to zero when the pressure rise across the fan vanishes, the power input will of course be considerably higher than this, the difference being accounted for by viscous losses in the fan blades. Although the power input to the fan was not measured, the tests at constant rotational speed extended between values of μ of 0 and 0.35 and Fig.6 suggests that it is quite feasible that the power input was actually constant over this range as would appear to be the case from the fact that it was unnecessary to adjust the fan speed-control trimmer.

The ideal power output coefficient shown in Fig.6 is intended only to be a guide to fan power requirements. Although an underestimate, it should not be far from the input power coefficient at low values of μ where the fan efficiency should be high. However under hovering conditions the static thrust factor of merit ζ defined as $C_T/(2K_p)^{2/3}$ is only equal to 1.00 according to the values of Figs.2 and 6. This compares with the maximum possible ideal value for a shrouded fan, $2^{1/3}$ or 1.26, and with the value 1.01 actually observed on a fan wing by Gregory and Walker[5] where the power input was obtained from torque measurements and included losses in the fan. It is possible that the static lift developed by the wing is reduced by tunnel constraint and ground effect.

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*Traverses taken at a value of μ of 0.2 with an exit cascade fitted to give 30° rearward deflection of the jet have indicated an 18% increase in K_p (actually only 10% increase above the smooth curve) and a small reduction below the measured value when both an entry and exit cascade were present. For the purposes of the ensuing calculations, therefore, the fitting of an exit cascade has also been assumed not to affect the power requirements of the fan.

5.3 The ideal output power ratio for the plain wing

Using the smoothed values of fan output power suggested by Fig.6, the ideal output power ratio has been calculated from the wind-tunnel tests for a variety of conditions in horizontal motion ($\Gamma = 0$). The thrust engine actuator disc area has been taken as either equal to, one half of, or one fifth of the fan area so that the effects of its variation could be examined.

Fig.7 shows the ideal power output ratio for the case of zero acceleration and with thrust actuator area equal to fan area. It should be noted that at positive non-zero incidences where the drag in hover is non-zero and thrust is required to balance the machine, the power output of the thrust engine is quite small compared with the output of the lifting fan. When speed is increased slowly at zero incidence a large hump is observed in the ideal power requirements. This, however, is completely eliminated in transitions carried out at incidences above about 6°, and the power requirements are least, for this particular wing, at 12°, the highest incidence at which tests were carried out. The thrust power and hence the total power are somewhat increased at all speeds by reduction in thrust actuator area. This is indicated by Fig.8, which also shows the effect on the total power requirements of stipulating an 0.3 g horizontal acceleration. Changes in overall power requirements are entirely due to changes in the thrust engine power as the fan power is independent of the thrust engine and is also assumed not to be affected by the horizontal acceleration.

It can be seen from Fig.8 that for this particular wing, reduction in thrust engine actuator disc area from 1 to $\frac{1}{2}$ to $\frac{1}{5}$ of the fan area successively increases from 6° to 8° to 12° the value of the incidence at which it is necessary to carry out transition in order to avoid the total power output exceeding that spent when hovering, and that these incidences differ from the slightly lower incidence, 4°, at which an increase in fan rotational speed during transition is just avoided. The principal effect of including an 0.3 g horizontal acceleration is to increase the thrust required by approximately 0.3 W in all conditions, and although the tests were not carried out above 12°, it would appear that the effect of the acceleration is to add a further 4° to the transition incidence which just avoids intermediate power requirements from exceeding those at the start.

These transition power requirements refer to a horizontal flight path ($\Gamma = 0$). An inclination of the flight path differing slightly from zero can be seen (equations (5) and (6)) to be largely equivalent in its effect to an additional acceleration equal to $g \sin \Gamma$.

5.4 The effect of an exit cascade

Wind-tunnel tests have been carried out at zero incidence with a cascade of 12 flat plate vanes each of 1.1 in. chord fitted on the efflux side of the fan duct with their hinges in the plane of the lower surface. The effect on fan-speed parameter required to support the wing is shown in Fig.9 and on the drag/lift ratio in Fig.10. Under static conditions, the intercepts of Fig.10 are closely equal to $\cot \beta$ for up to 30° deflection of the cascade ($\beta = 60°$) thus indicating that the cascade is suitably deflecting the fan efflux. At larger angles of deflection $\cot \beta$ is exceeded, though this may be due to an interaction between the emergent jet and the lower surface resulting in a loss of lift. The effect of the cascade on the mass flow through the fan was only investigated with 30° deflection of the jet and with V_T/V_F equal to 0.3. At constant fan rotational speed, the presence of the cascade then reduced the mass flow by 8%.

The balance between loss in lift and the production of thrust which results from the deflection of the cascade and is implicit in Figs.9

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and 10 cannot be readily assessed at other than zero forward speed without recourse to power considerations. Fig.11 shows the effect of exit cascade deflection on the ideal output power ratio for the case of thrust actuator area equal to fan area. The denominator of the output power ratio refers to the power required for hovering at zero incidence without the cascade fitted, so that the departure of the value of the output power ratio from unity when the cascade is fitted (without deflection) in the hovering case reflects a small reduction in the flow through the fan in these conditions. The calculation of the output power ratio could not be completed for conditions where the thrust required from the thrust engine became negative. Nevertheless, at values of the forward-speed parameter less than 2.5, a very small saving in total power is obtained with 10° deflection of the efflux, but this vanishes with 20° or higher deflection.

The effects of reduction in thrust actuator area and of 0.3 g horizontal acceleration are shown in Fig.12. The latter enables the calculation to be completed over a wider range of conditions, whilst reduction in thrust actuator area to $\frac{1}{5}$ of the fan area so reduces the efficiency of the propulsive mechanism that it is now seen to be worthwhile to obtain thrust by deflecting the fan efflux up to about 30°. It is noteworthy that this result is obtained despite the forward location of the fan at 0.354 chord with consequent severe adverse interaction resulting in loss of lift at forward speeds.

The experimental measurements with cascades were not carried out at other than 0°, but it seems likely that similar results to those of Fig.12 would appertain to the non-zero incidence curves of Fig.8, though this obviously requires verification.

5.5 Discussion of results

It is thus seen that for the present model with an assumed thrust actuator of $\frac{1}{5}$ the fan area, Fig.8 shows that (with fan efflux undeflected) it is better to carry out transition at as high an angle of incidence as possible. This is because the fan is so far forward, which coupled with the much higher value of the fan loading than the wing loading (A_W/A_F high)* results in severe adverse interaction effects so that it pays to shut down the fan as rapidly as possible. Fig.12, however, shows that moderate deflection of the fan efflux is beneficial when the thrust engine loading is assumed to be itself much higher than the fan loading (A_F/A_T high), in which case the fan speed would be reduced at a much later stage in transition. These conclusions are peculiar to the present fan-wing combination. Much further work is required to determine the similarities and differences between these results and those pertaining to other fan-wing systems having relative values of the parameters A_W, A_F, A_T, which design studies suggest are of practical interest.

6. Conclusions

A method is given for representing the results of wind-tunnel tests of fan wings in a non-dimensional form which is suitable for the analysis of transition motions.

As an example, the results of tests of a rectangular wing of aspect ratio 1 with fan located at 0.354 chord are displayed in the new form. For this particular wing it appears that transition from hovering to wing-supported flight is best made at at least 12° incidence, the highest incidence at which tests were carried out.

Calculations/

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*Apart from interaction effects, a high value of A_W/A_F is desirable, as it implies a high value of fan efflux velocity/minimum flight speed which minimises the peak value of the momentum drag[6].

Calculations based on the wind-tunnel results show how the power requirements for this wing are modified by variation of thrust engine loading, and also by an 0.3 g horizontal acceleration and by deflection of the fan efflux by a cascade of flat plate vanes.

Further research is required to ascertain how much these particular results are affected by variations in wing and fan geometry.

Acknowledgement

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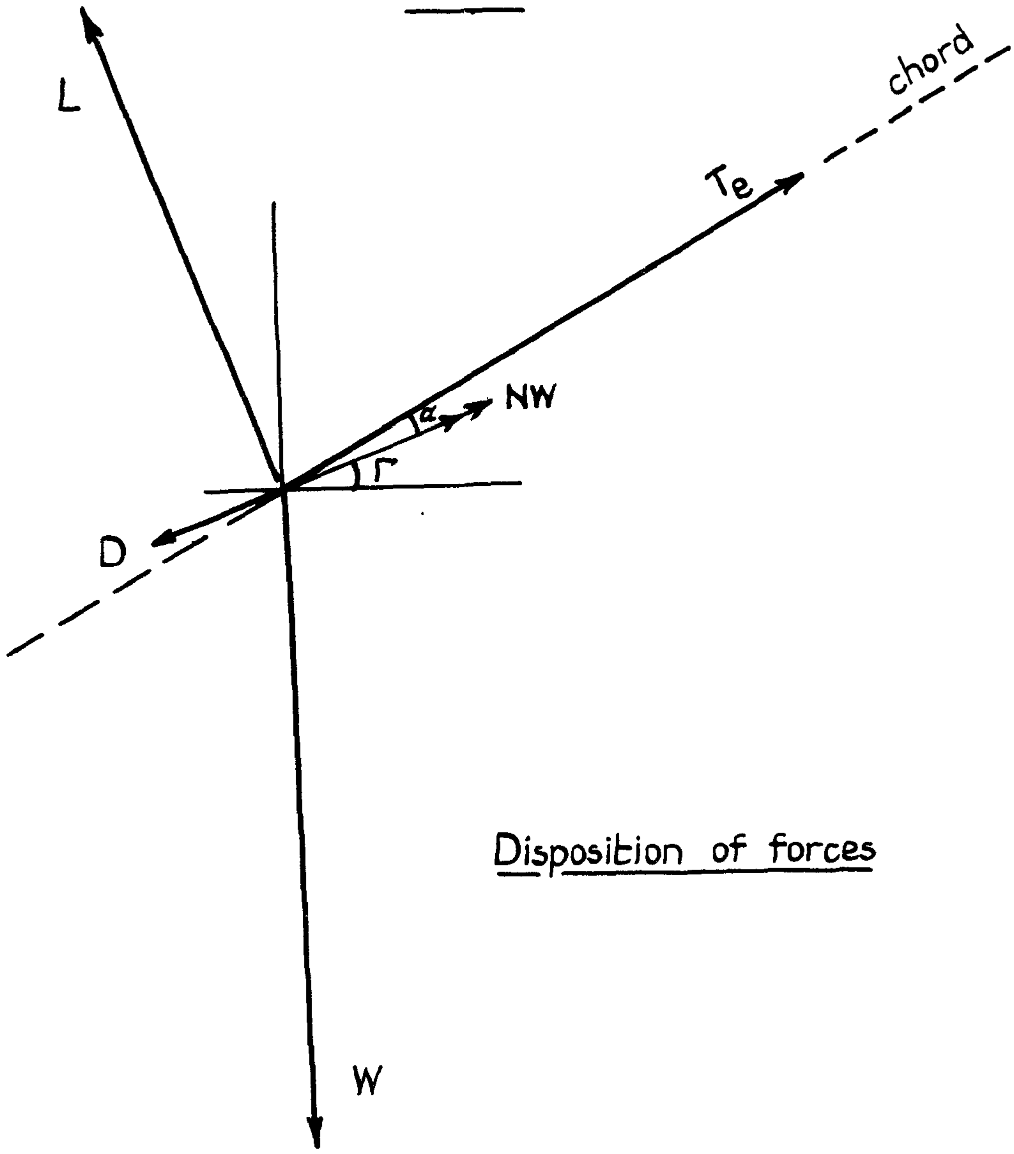
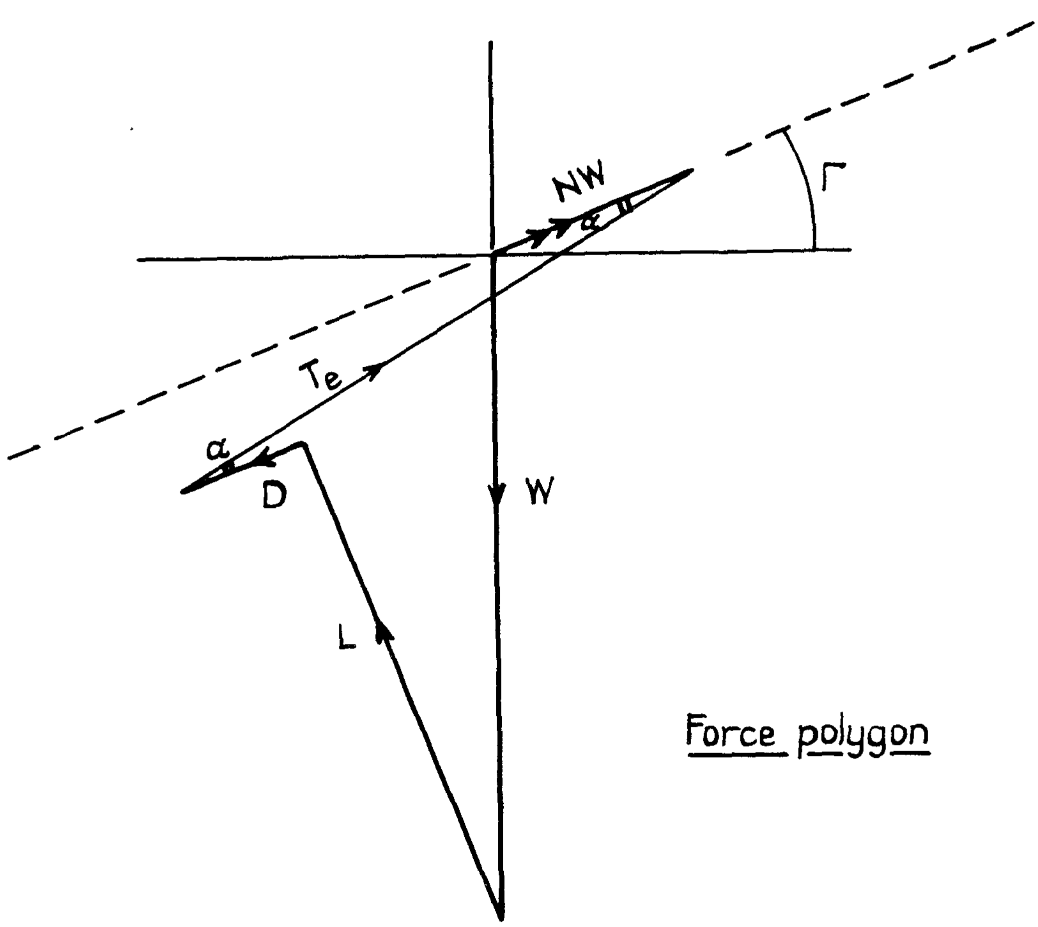
FIG. 1.

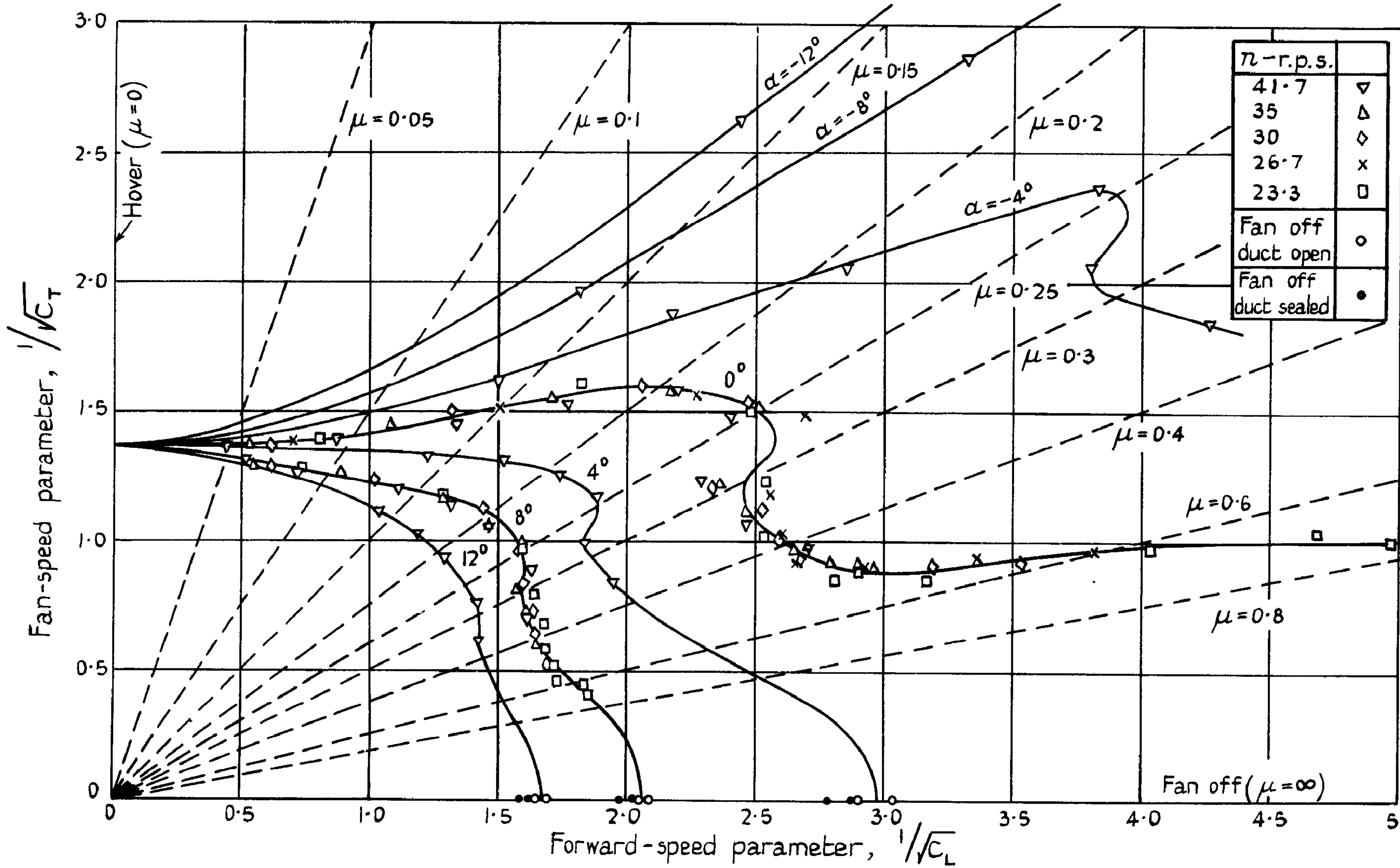


Disposition of forces



Force polygon

Forces and force polygon for a straight-line acceleration.

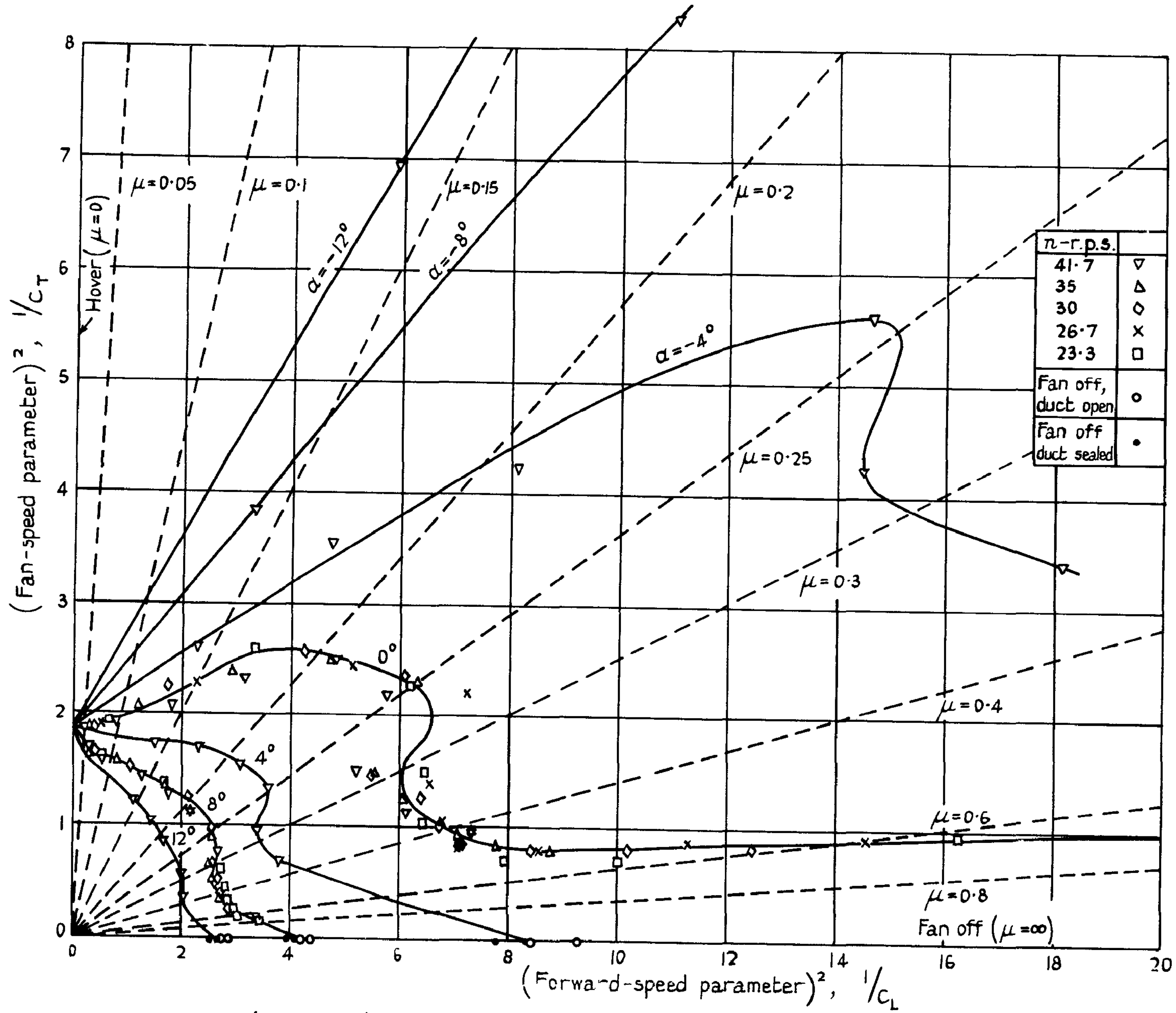


Variation of fan-speed parameter with forward-speed parameter and incidence for aspect ratio-1 wing with fan at 0·354 chord.

$A_W = 31{\cdot}1$ sq ft, $A_F = 0{\cdot}708$ sq ft, μ = Forward speed / Fan blade tip speed = $V_T / \pi n d$

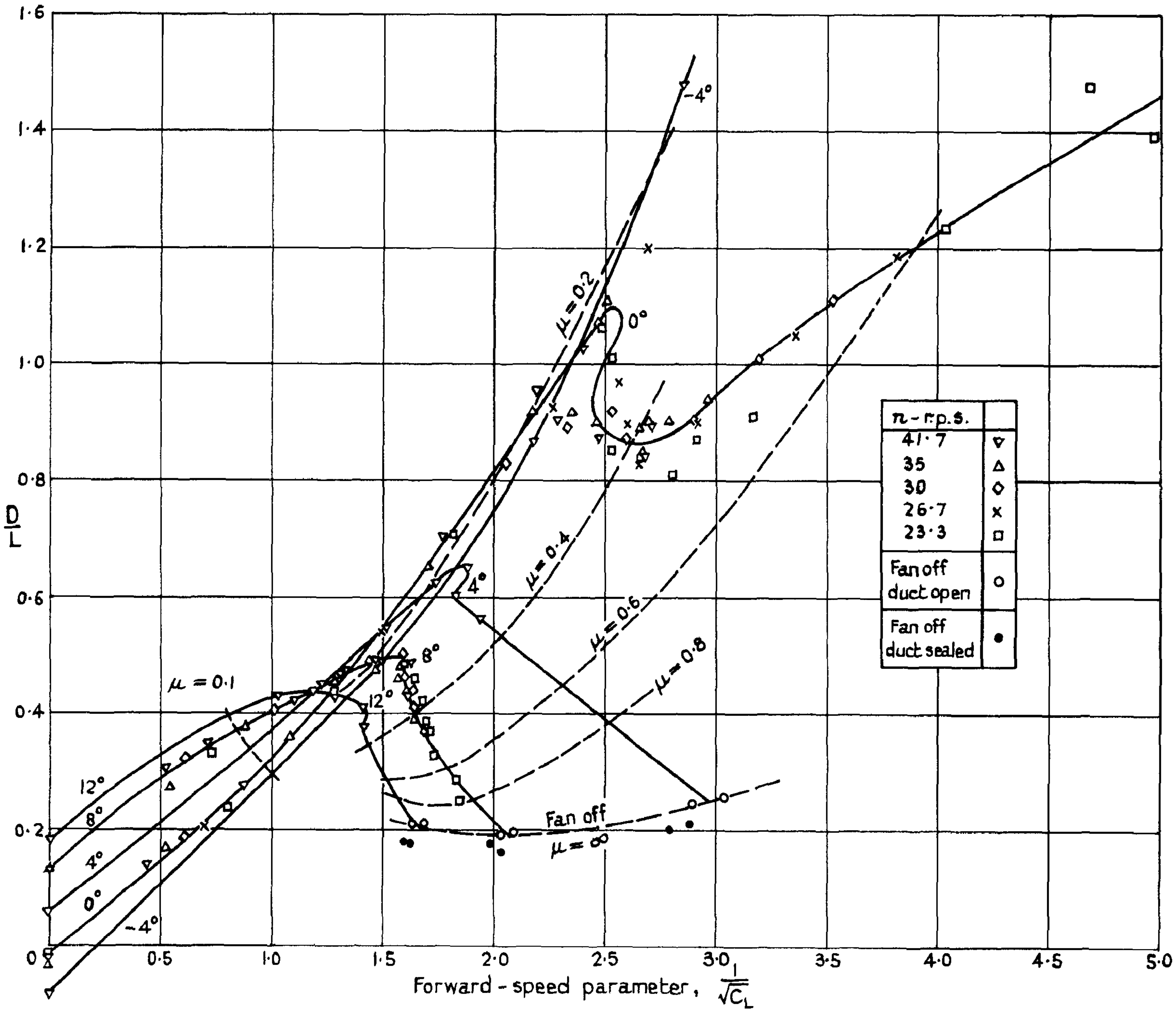
$\pi n d \sqrt{\tfrac{1}{2} \rho A_F / L} = 1/\sqrt{C_T}$ $\qquad V_T \sqrt{\tfrac{1}{2} \rho A_W / L} = 1/\sqrt{C_L}$

FIG. 2.



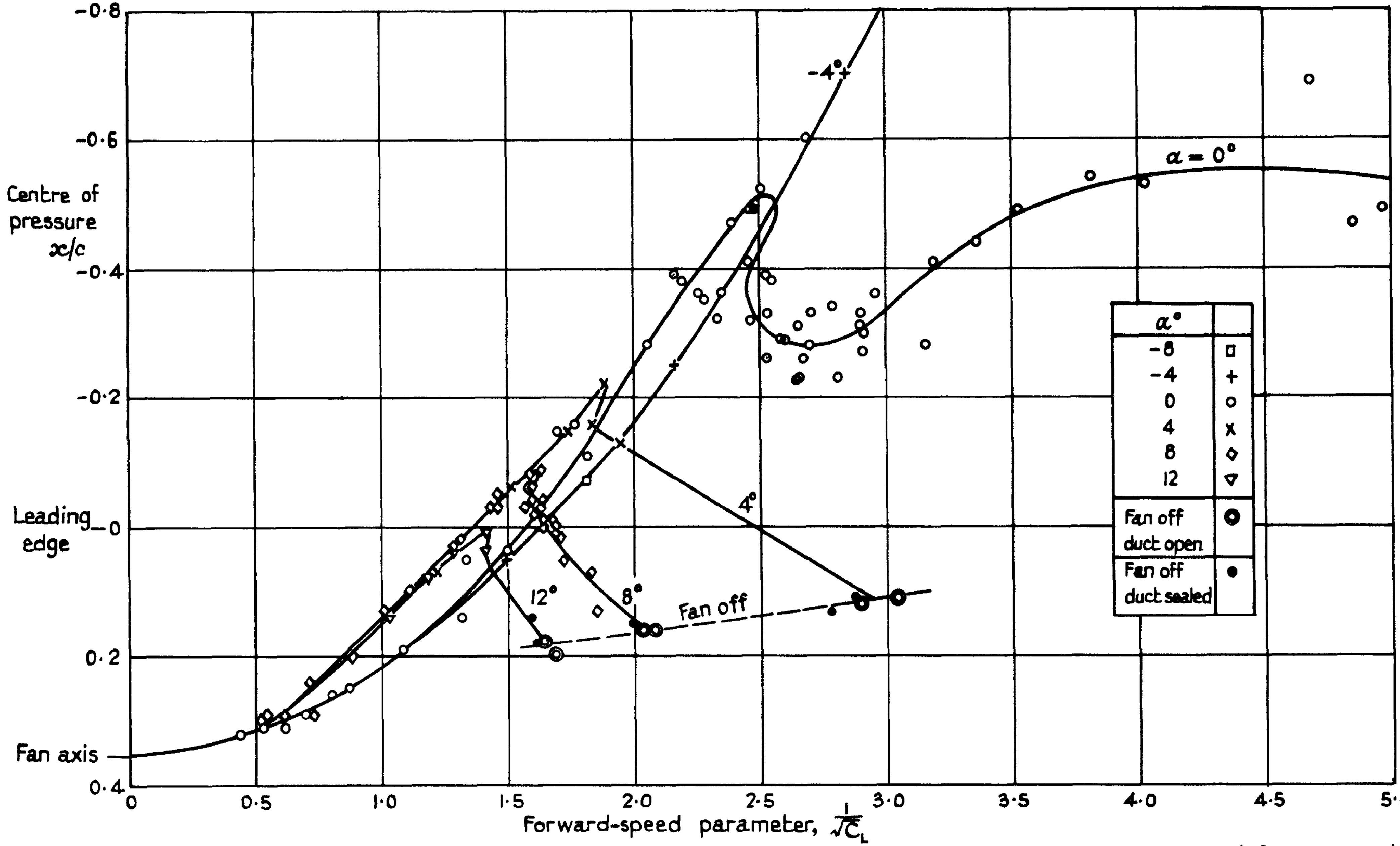
Variation of $1/C_T$ with $1/C_L$ and α for aspect ratio-1 wing with fan at 0·354 chord.

FIG. 3.



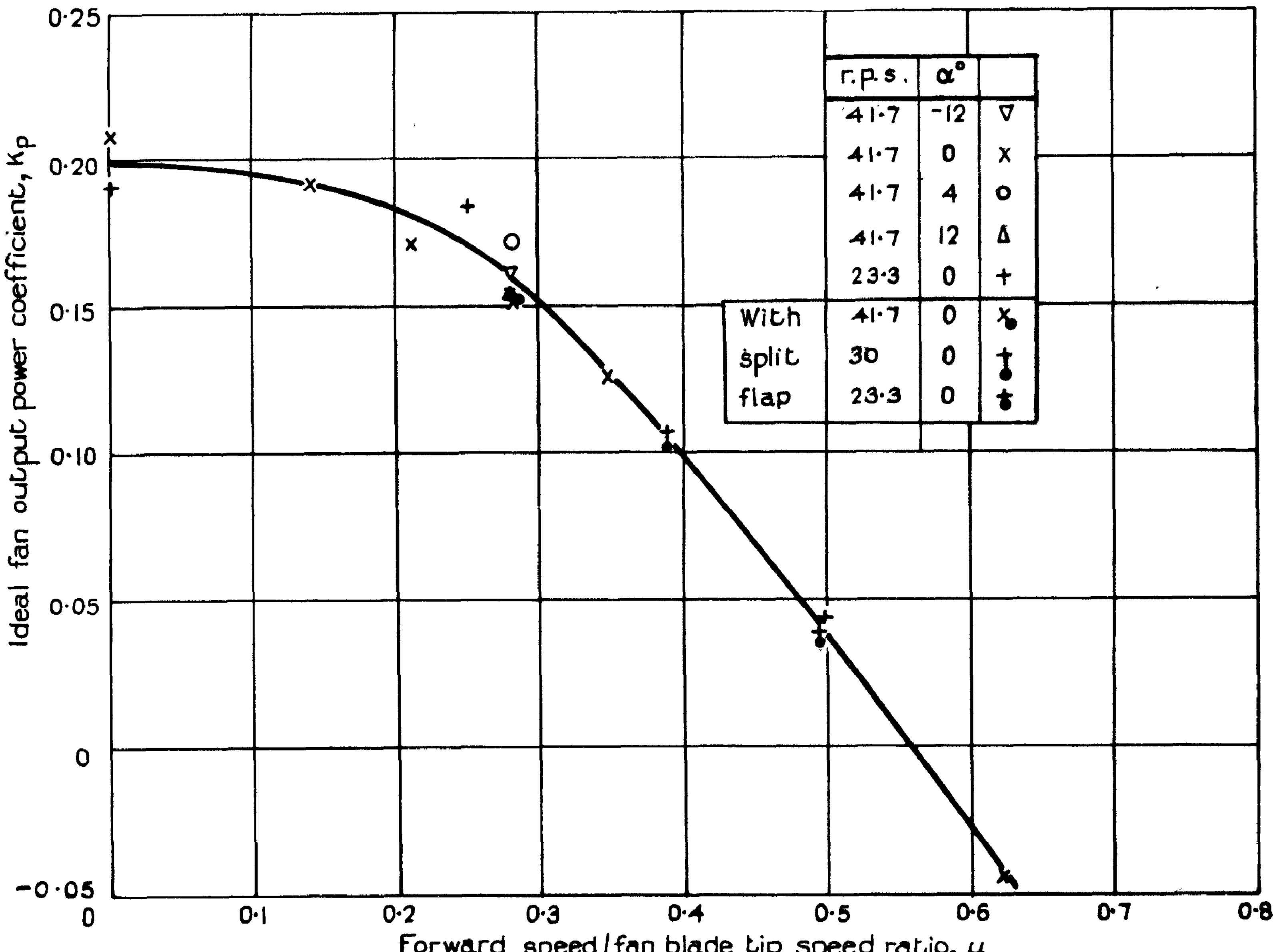
Variation of drag/lift ratio with forward-speed parameter and incidence for aspect ratio -1 wing with fan at 0·354 chord

FIG. 4.



Variation of centre of pressure position with forward-speed parameter and incidence for aspect ratio-1 wing with fan at 0·354 chord.

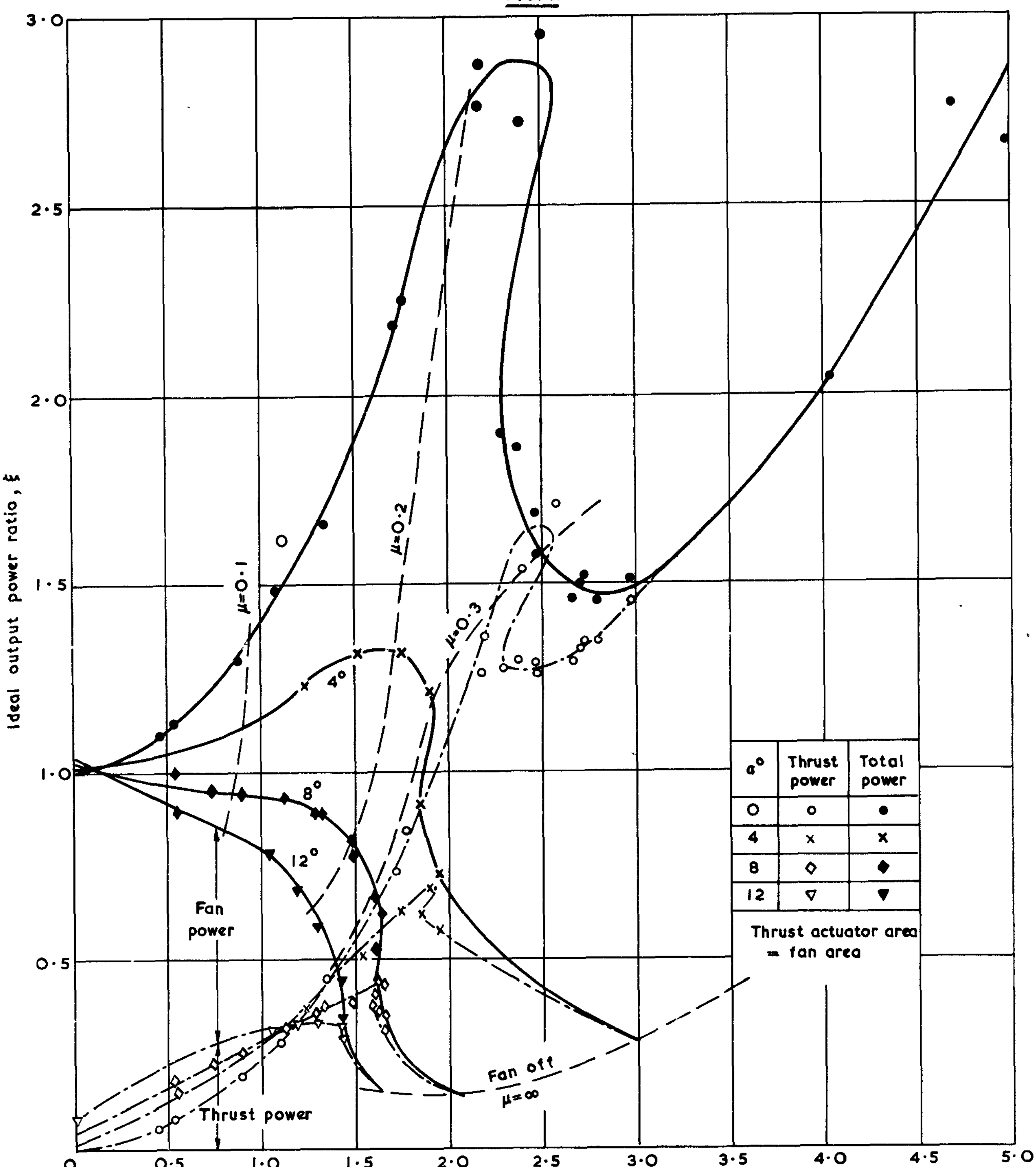
FIG. 5.



Variation of ideal fan output power coefficient with forward speed / fan blade tip speed ratio for fan in aspect ratio - 1 wing. "Ideal" signifies no entry losses.

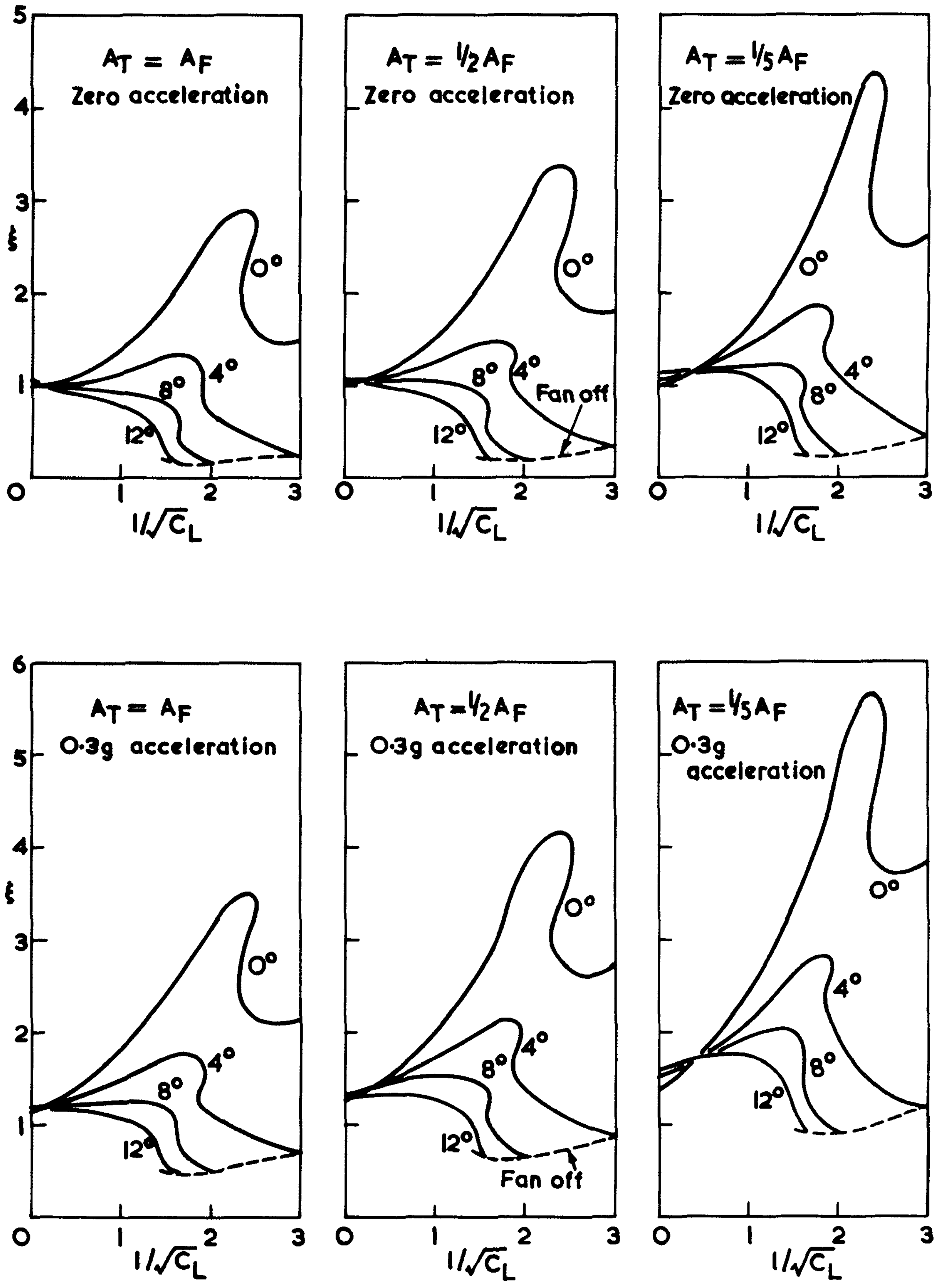
FIG. 6.

FIG. 7.

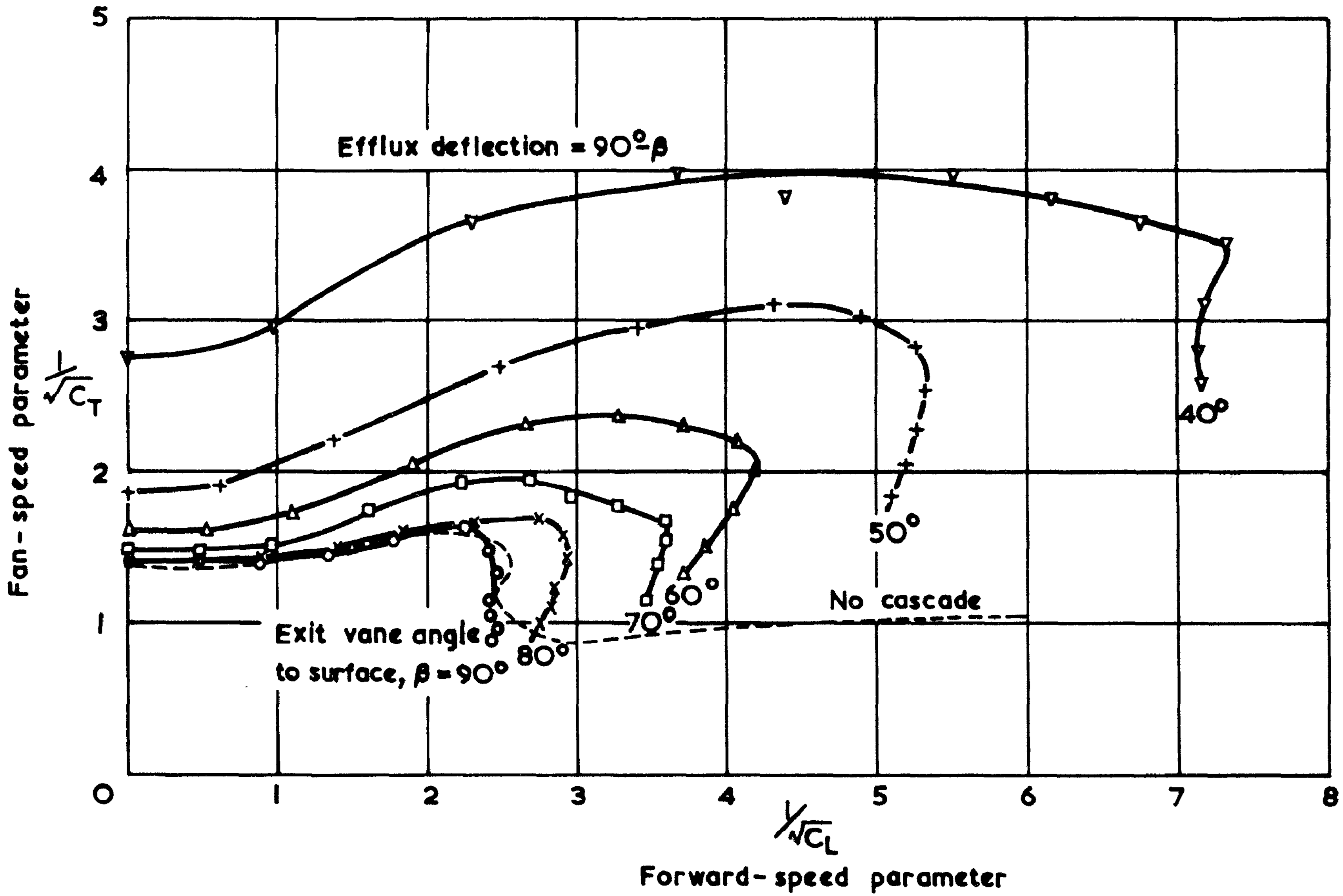


Variation of ideal output power ratio with forward-speed parameter and incidence for aspect ratio-1 wing with fan at 0·354 chord (Thrust actuator area = fan area)

FIG. 8



Effect of changes in thrust actuator area and of horizontal acceleration on ideal power output ratio



Effect of exit cascade on fan-speed ~ forward-speed relation at zero incidence

FIG. 9

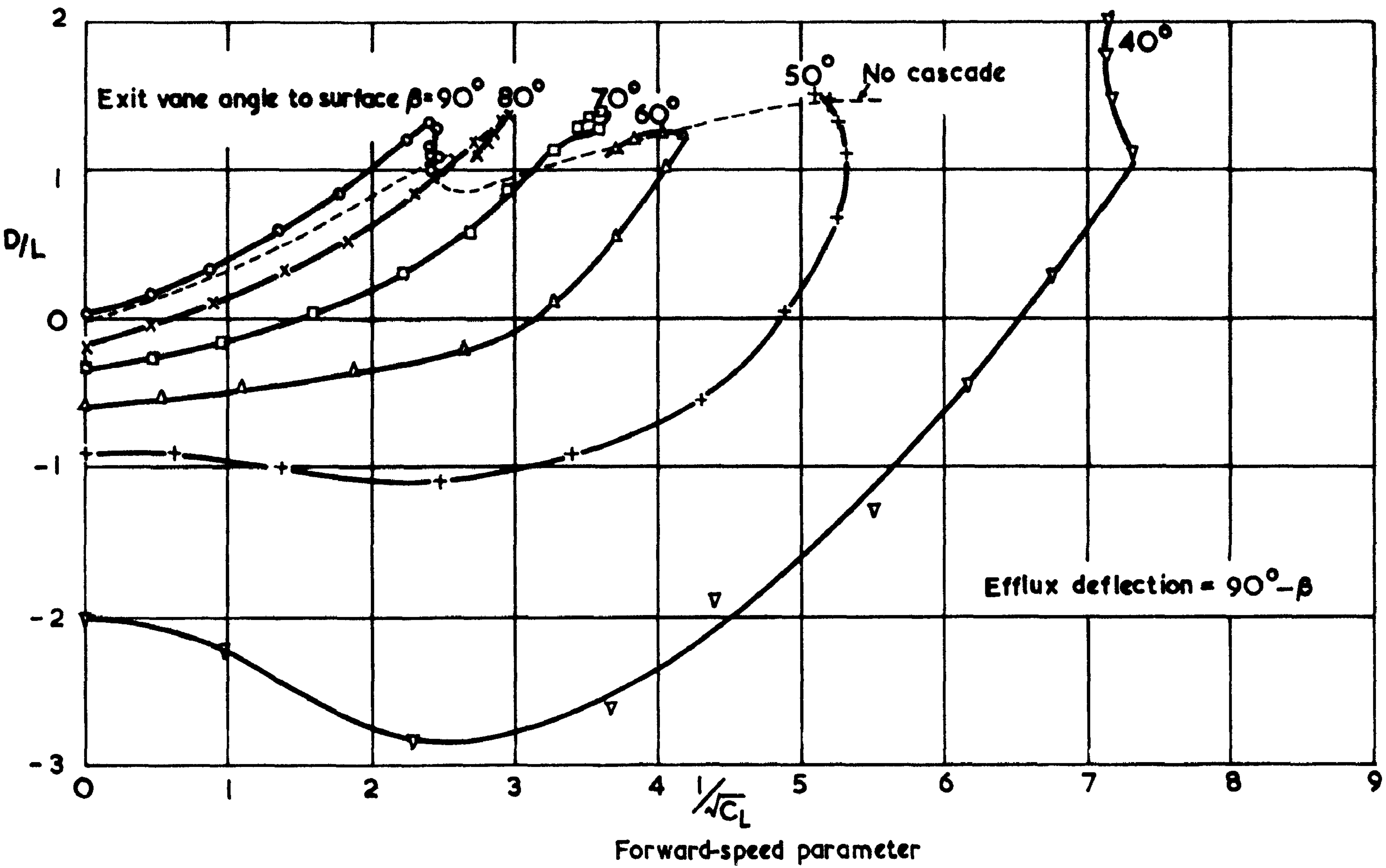
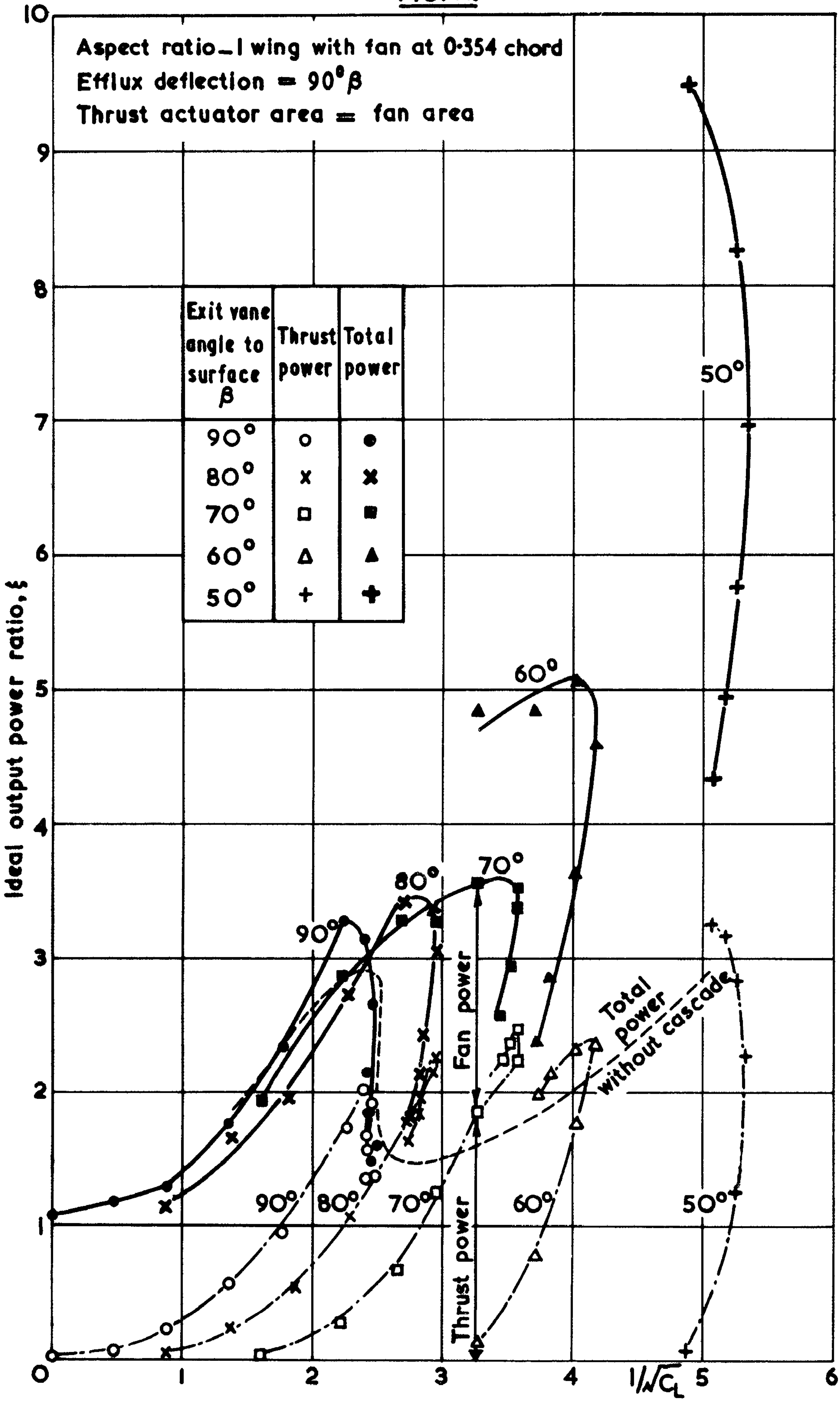


FIG. 10

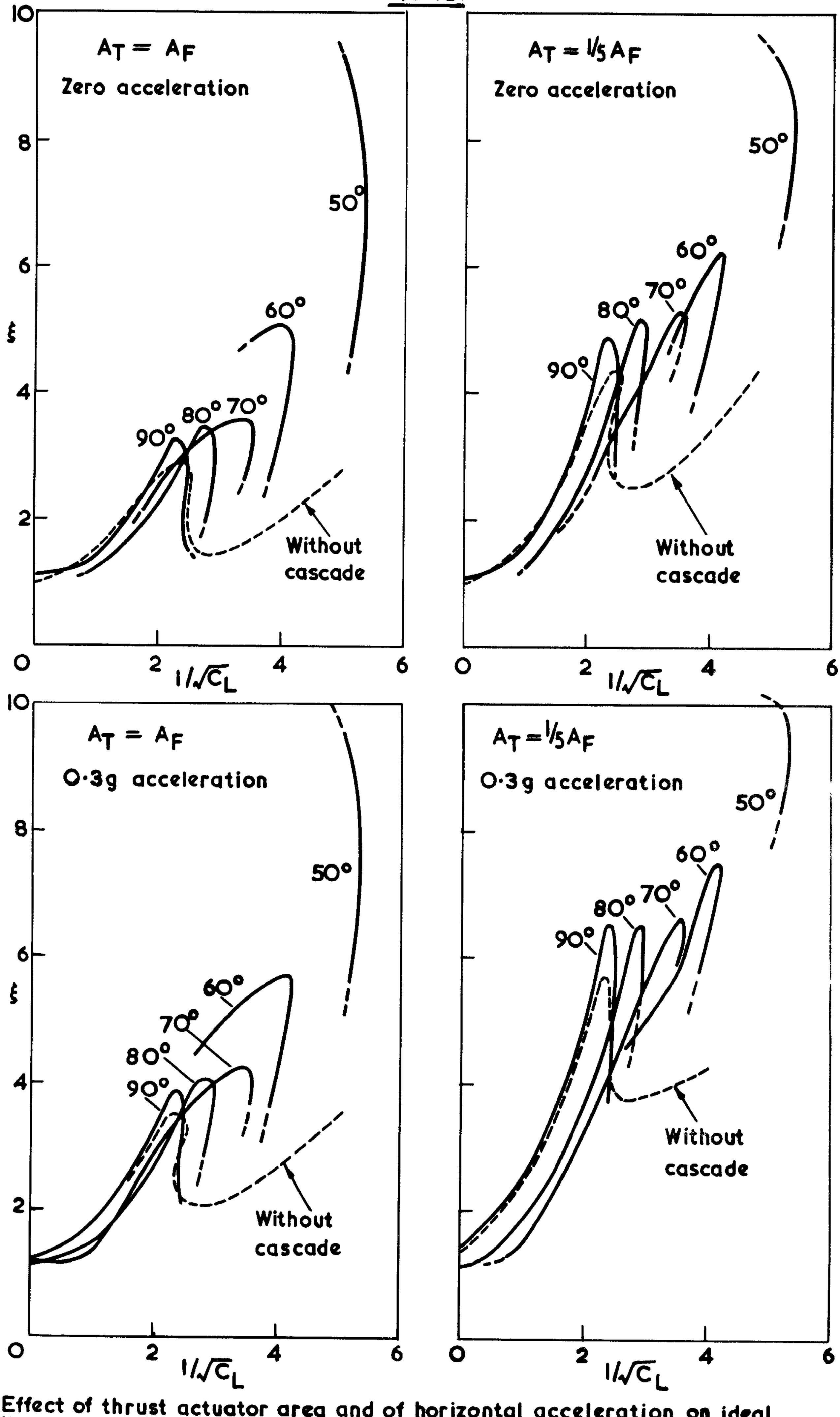
Effect of exit cascade on drag at zero incidence

FIG. 11.



Effect of exit cascade on ideal output power ratio at zero incidence

FIG. 12.



Effect of thrust actuator area and of horizontal acceleration on ideal power output ratio at 0° incidence with exit cascade

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