THE ANALYSIS OF PROPELLER-WING FLOW INTERACTION

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SUMMARY

Theoretical methods are developed for calculating the interaction of a wing both with a circular slipstream and with a wide slipstream such as might be produced if the slipstreams of several propellers merged. To simplify the analysis rectangular and elliptic jets are used as models for wide slipstreams. Standard imaging techniques are used to develop a lifting surface theory for a static wing in a rectangular jet. The effect of forward speed is analyzed for a lifting line in an elliptic jet, and a closed form solution is found in the case when the wing just spans the foci of the ellipse. A continuous wide jet is found to provide a substantially greater augmentation of lift than multiple separate jets because of the elimination of edge effects at the gaps. Calculations based on these methods show good correlation with experimental data for wings without flaps, but deflection of flaps seems to result in a greater turning effectiveness than might be expected from the theory.

INTRODUCTION

The need for V/STOL aircraft to relieve air traffic congestion is becoming increasingly apparent. Interest therefore has been renewed in predicting the influence of propeller-wing flow interaction on the aerodynamic characteristics of deflected slipstream and tilt wing aircraft.

The lift of a wing spanning a single circular slipstream has been quite extensively studied. Early investigators used lifting line theory (refs. 1, 2). Later slender body theory was introduced to treat the case when the aspect ratio of the immersed part of the wing is small (refs. 3, 4). Neither of these theories agreed well with experimental results. Lifting surface theories were developed by Rethorst (ref. 5), using an analytical approach, and Ribner and Ellis (ref. 6), using a numerical approach. These give better agreement at the expense of lengthy computations. Only Sowydra (ref. 7) has attempted to allow for the deflection of the slipstream boundary.

Rethorst's method has been extended to treat approximately a wing in several separate slipstreams (ref. 8). None of these investigations, however, has allowed for the possibility of the slipstreams from several propellers merging to form a single wide jet. It can be expected that the elimination of the gaps would lead to an increase in efficiency by allowing the circulation to be maintained continuously across the span. Studies of wide jets were initiated by De Young (ref. 9), and have been continued by the present author. Results of calculations both for circular slipstreams from isolated propellers and for wide slipstreams are presented in this paper.

FORMULATION

The general case to be considered is a wing in a slipstream generated by one or more propellers with an external flow due to forward motion of the wing. The following simplifications are made:

(1) The fluid is inviscid and incompressible.

(2) Rotation in the slipstream is ignored and it is treated as a uniform jet.

(3) The jet boundary is assumed to extend back in a parallel direction.

Under these assumptions the perturbation velocity due to the wing can be represented as the gradient of a velocity potential which satisfies Laplace's equation (fig. 1). At the boundary it is necessary to maintain continuity of both pressure and the transverse flow angle. Let V_j and V_o be the undisturbed velocities in the slipstream and the external flow. Then if Bernoulli's equation is linearized, the boundary conditions can be expressed as

$$\phi_j = \mu\phi_o \tag{1}$$

$$\mu \frac{\partial\phi_j}{\partial n} = \frac{\partial\phi_o}{\partial n} \tag{2}$$

where ϕ_j is the interior potential, ϕ_o is the exterior potential, and μ is the velocity ratio

$$\mu = \frac{V_o}{V_j} \tag{3}$$

ANALYTIC METHODS

To restrict the complexity of the calculations it is desirable to use the simplest possible analytical models. Two models of wide slipstreams have been found to be amenable to analysis. In the first the slipstream is represented as a rectangular jet. A lifting surface theory can then be developed which is exact only in the static case. In the second the slipstream is represented by an elliptic jet. A quite simple lifting line theory can then be developed which is valid for the entire speed range. A simplified lifting surface theory for a circular slipstream can also be developed with the aid of calculations for a square jet.

Lifting Surface Theory for a Rectangular Jet

In the static case ($V_o = 0$) only the first boundary condition (1) remains to be satisfied. A rectangular jet can then be treated by the method of images as in the theory for an open wind tunnel (ref. 10). Since the wing is large compared with the jet, it is necessary to allow for the nonuniformity of the additional downwash due to the jet boundary. When the wing spans the jet, the influence of the jet dimensions can be conveniently represented by the single parameter jet aspect ratio

$$AR_j = \frac{B}{H} \tag{4}$$

where B and H are the jet width and height.

The wing is represented by a distribution of horseshoe vortices (fig. 2). For each horseshoe vortex the boundary condition can be satisfied over the whole jet surface in three dimensions by introducing a doubly infinite set of images into a lattice formed by extending the rectangle containing the jet (fig. 3). The images thus give the correct longitudinal variation of the downwash, and a lifting surface theory can be developed. It is expedient to use Weissinger's simplified method in which the bound vorticity is concentrated at the 1/4 chord line, and the boundary condition that the flow must be tangential to the surface is satisfied only at the 3/4 chord line. If a finite number of vortices are used to represent the wing, the determination of the lift can be reduced to the solution of a set of algebraic equations. The downwash angle at the nth spanwise control point due to unit circulation at the mth spanwise station can be represented as an influence coefficient $A_{nm} + R_{nm}$, where A_{nm} is the contribution of the original vortex and R_{nm} is the contribution of the images. If Γ_m is the circulation at the mth station, the total induced angle at the nth control point is then

$$\alpha_n = \sum (A_{nm} + R_{nm})\Gamma_m \tag{5}$$

When one applies the boundary condition that the induced angle must equal the wing surface angle, equation (5) becomes a set of equations for the circulation.

It is convenient to distribute the horseshoe vortices so that their lateral limits are at the span fractions $\cos[(2m-1)\pi/2N]$ and their strengths represent the circulation at the points $\cos(m\pi/n)$. This permits previously developed methods (ref. 11) to be used for determining the free-stream influence coefficients A_{nm}. The interference influence coefficients R_{nm} have then each to be determined by summing a double series. The summation can be simplified by evaluating the interference downwash w_{jo} and its slope dw_j/dx at the 1/4 chord line and using the approximation

$$w_j = w_{jo}\left\{1 + \frac{x}{\sqrt{[w_{jo}/(dw_j/dx)]^2 + x^2}}\right\} \tag{6}$$

When the aircraft has a forward speed, it is unfortunately not possible to satisfy the two boundary conditions (1) and (2) by introducing images. The effect of forward speed may be treated approximately, however, by multiplying the interference downwash distribution and therefore the influence coefficients R_{nm} in equation (5) by a scalar strength factor P. The correct answers are obtained for the static case and the free stream by setting $P = 1$ and $P = 0$ at these limits. At intermediate velocity ratios, it appears from an examination of the results of lifting line theory for an elliptic jet that a suitable strength factor is

$$P = \frac{1 - \mu^2}{1 + AR_j\mu^2} \tag{7}$$

Lifting Line Theory for an Elliptic Jet

For the purpose of developing a lifting line theory a single horseshoe vortex may be resolved into a pair of infinite line vortices and an antisymmetric pair of horseshoe vortices (fig. 4). The antisymmetric part produces no downwash at the lifting line, and it is therefore only necessary to represent the two-dimensional part of the potential. Let ϕ_v represent the potential of a vortex distribution in the absence of the jet boundary, and let $\Delta\phi_j$ and $\Delta\phi_o$ be the interior and exterior perturbation potentials due to the boundary, so that

$$\phi_j = \phi_v + \Delta\phi_j \tag{8}$$

$$\phi_o = \phi_v + \Delta\phi_o \tag{9}$$

These potentials can be represented as series

$$\phi_v = \sum A_n e^{-n\xi} \sin n\eta \tag{10}$$

$$\Delta\phi_j = \sum B_n \sinh n\xi \sin n\eta \tag{11}$$

$$\Delta\phi_o = \sum C_n e^{-n\xi} \sin n\eta \tag{12}$$

where ξ and η are elliptic coordinates

$$y + iz = a \cosh(\xi + i\eta) \tag{13}$$

and the boundary is at $\xi = \xi_o$ (fig. 5). Then introducing the boundary conditions (1) and (2), and equating coefficients, it is possible to solve for B_n and C_n in terms of A_n as

$$B_n = - \frac{1 - \mu^2}{1 + \mu^2 F_n(\lambda)} \frac{2A_n}{[(\lambda + 1)/(\lambda - 1)]^n - 1} \tag{14}$$

$$C_n = - \frac{(1 - \mu)[1 - \mu F_n(\lambda)]}{1 + \mu^2 F_n(\lambda)} A_n \tag{15}$$

where the ratio of width to height of the ellipse is

$$\lambda = \coth \xi_o \tag{16}$$

and

$$F_n(\lambda) = \coth n\xi_o = \frac{[(\lambda + 1)/(\lambda - 1)]^n + 1}{[(\lambda + 1)/(\lambda - 1)]^n - 1} \tag{17}$$

For a pair of vortices at (ξ_1, η_1) and $(\xi_1, -\eta_1)$ Tani and Sanuki (ref. 12) found that

$$A_n = \frac{2}{\pi n} \cosh n\xi_1 \cos n\eta_1 \tag{18}$$

The influence of forward speed on the interior potential is represented by the factor $(1 - \mu^2)/[1 + \mu^2 F_n(\lambda)]$ which reduces to $(1 - \mu^2)/(1 + \lambda\mu^2)$ for the first term.

When the wing extends exactly between the foci of the ellipse (fig. 6), a simple closed form solution can be obtained. The first term of the series represents a uniform downwash between the foci, and thus for a wing with an elliptic lift distribution only this term remains. For a given lift the effect of the jet is then simply to increase the induced downwash by the factor

$$\frac{\lambda + \mu^2}{1 + \lambda\mu^2} \tag{19}$$

The wing thus behaves as if its aspect ratio were divided by this factor. This is a generalization of a result obtained by Glauert (ref. 13) for open wind tunnels.

It is also possible to develop a slender-body theory for a wing in an elliptic jet (ref. 14). An extension to a lifting surface theory would require the representation of the antisymmetric part of the potential as an expansion in Mathieu functions.

Approximate Lifting Surface Theory For Circular Jets

For a circular jet the two-dimensional part of the interference potential due to a horseshoe vortex can be represented by images at the inverse points. The antisymmetric part can be represented as an expansion in Bessel functions (ref. 5). The results of wind-tunnel theory, however, indicate that the ratio of the slope of the downwash to the downwash at the load line is nearly the same for circular and square jets. Thus the slope can be approximated by multiplying the downwash at the load line for the circular jet by the ratio for the square jet. Then the longitudinal variation of downwash can be estimated by equation (6). Thus the need to determine the antisymmetric potential is obviated and the calculations can be simplified.

Results of Computer Calculations

Calculations for rectangular wings spanning rectangular jets have been made by computer, using 8 vortices per semispan to represent the wing. Typical results are shown in figures 7 to 9.

Figure 7 shows the effect of jet aspect ratio on lift and induced drag over the speed range for wings of aspect ratio 2 and 4. Forward speed is represented by the velocity ratio μ. In order to obtain meaningful values in the static case the lift and drag coefficients are referred to the jet velocity. With this convention the lift slope decreases as μ decreases because of the reduction in the external flow. Also for a given lift the induced drag increases. The wing is assumed to span the jet so that an increase in jet aspect ratio represents a decrease in jet height. It can be seen that the jet effects are accentuated as the jet becomes shallower.

When the angle of attack α is small and the aircraft is static, the jet deflection angle θ equals the ratio of lift to thrust. Figure 8 shows the static turning effectiveness $\theta/\alpha = L_\alpha/T$. For a given jet aspect ratio the turning effectiveness increases toward a limiting value as the wing chord is increased or its aspect ratio reduced. There is not much of a fall-off from this limiting value until $AR > AR_j$, or the wing chord is less than the jet height. The turning effectiveness also increases as the jet aspect ratio is increased and the jet becomes shallower: it is easier to deflect a flow which is close to the wing.

Figure 9 illustrates the influence which these trends could have on a design. The static performance of a wing in a large square jet is compared with its performance in a single wide jet of aspect ratio 4. In the large jet $L_\alpha/T = 0.365$. In the wide jet it is increased to 0.835. Since the disc loading of the wide jet is four times that of the large jet, the thrust for a given power input would be reduced. According to ideal actuator theory it would be a fraction $(1/4)^{1/3} = 0.630$ of the thrust of the large jet. Despite this the lift in the wide shallow jet would still be greater. It thus appears that it might well be advantageous to use several small propellers of high disc loading on each semispan, provided they could be placed close enough for their slipstreams to merge without incurring too large a loss of efficiency.

USE OF APPARENT MASS ARGUMENTS TO DERIVE SIMPLE APPROXIMATE FORMULAS

The form of the solution for a wing spanning the foci of a elliptic jet suggests a general approach to obtaining quick approximate answers. In a free stream an elliptic wing acts as if it deflected an apparent mass equal to that captured by a circle containing its tips through a uniform downwash angle. In a jet the reduction in the exterior velocity below the jet velocity causes the wing to encounter a smaller mass flow, so it can be expected to deflect a smaller apparent mass through a larger downwash angle. This is equivalent to a reduction in the effective aspect ratio from AR to

$$AR_\mu = \frac{AR}{1 + p}$$

where p is the fractional increase in downwash. Then according to lifting line theory the ratio of the lift slope to the lift slope in a free stream would be

$$\frac{C_{L_{\alpha_\mu}}}{C_{L_{\alpha_1}}} = \frac{2\pi/[1 + (2/AR)]}{2\pi/\{1 + [2(1 + p)/AR]\}} = \frac{AR + 2}{AR + 2(1 + p)}$$

It has been found that the results of detailed calculations for rectangular wings just spanning the slipstream can in fact be closely approximated by formulas of this type. If the free stream, the static case, and intermediate velocity ratios are denoted by subscripts 0, 1, and μ, the following formulas may be used for rectangular jets:

$$\frac{C_{L_{\alpha_o}}}{C_{L_{\alpha_1}}} = \frac{AR + 2}{AR + 2AR_j + [2.5/(1 + AR)]} \tag{20}$$

$$\frac{C_{L_{\alpha_\mu}}}{C_{L_{\alpha_1}}} = \frac{1}{1 + [(C_{L_{\alpha_1}}/C_{L_{\alpha_o}}) - 1][(1 - \mu^2)/(1 + AR_j\mu^2)]} \tag{21}$$

Also if r denotes the induced drag factor $C_D/C_L{}^2$

$$\frac{r_o}{r_1} = 0.76(AR_j + e^{-AR_j}) + 0.53 \tag{22}$$

$$\frac{r_\mu}{r_1} = \frac{(r_o/r_1) + [1 + AR_j - (r_o/r_1)]\mu^2}{1 + AR_j\mu^2} \tag{23}$$

These formulas are valid in the range $AR > (1/2)AR_j$, or wing chord less than twice the jet height. Similarly, for a rectangular wing spanning a circular jet the following formulas closely approximate the results of detailed calculations:

$$\frac{C_{L_{\alpha_o}}}{C_{L_{\alpha_1}}} = \frac{AR + 2}{AR + 3.54} \tag{24}$$

$$\frac{C_{L_{\alpha_\mu}}}{C_{L_{\alpha_1}}} = \frac{1}{1 + [(C_{L_{\alpha_1}}/C_{L_{\alpha_o}}) - 1][(1 - \mu^2)/(1 + \mu^2)]} \tag{25}$$

$$\frac{r_o}{r_1} = 1.68 \tag{26}$$

$$\frac{r_\mu}{r_1} = \frac{1.68 + 0.32\mu^2}{1 + \mu^2} \tag{27}$$

PREDICTION OF CHARACTERISTICS OF PRACTICAL CONFIGURATIONS

In order to estimate the lift of a propeller-wing combination at an angle of attack it is necessary to allow for the direct contribution of the propeller thrust, the propeller normal force due to the inclined inflow, and the change in the wing lift due to the propeller. The propeller slipstream has three principal effects on the wing: it increases the dynamic pressure, it alters the angle of attack, and it decreases the lift slope. All three effects must be estimated. The preceding analysis yields an insight into the last effect, but strictly only applies to wings completely contained in a jet. Assuming that the effect of a jet is small on the part of the wing outside the jet, it is, however, possible to make an estimate by using superposition. The increase in lift of the blown part of the wing, treated as if it were an independent planform, is added to the lift of the whole wing in a free stream. Along these lines a practical method has been developed for quick estimation of the characteristics of propeller-wing combinations, which gives good correlation with published experimental data. Two examples are shown in figures 10 and 11. All the aerodynamic coefficients are referred to the slipstream velocity, so that the static case is represented by $C_T = 1.0$, and the lift coefficient decreases as the thrust coefficient increases and the velocity ratio decreases. The profile drag was not calculated, so that the theoretical drag curves should be to the left of the experimental points. At high thrust coeffcients the apparent profile drag coefficient is reduced because the drag coefficient of sections outside the slipstream is referred to the higher velocity in the slipstream. It should also be noted that rotation of the slipstream has been ignored. Provided that the wing completely spans the jet, the increase in angle of attack on one side of the jet should be compensated by the decrease on the other side, so the total lift should be about the same, although its distribution is altered.

DIVERGENCE BETWEEN THEORY AND OBSERVED DEFLECTION OF SLIPSTREAMS BY FLAPS

An exact calculation by potential theory of the lift of flapped wings would require the use of a model with multiple lifting lines. If, however, the effect of deflecting flaps through an angle δ is regarded as equivalent to an increase in the effective wing angle of attack α, the present method may be used, given suitable information about the effect of the jet on the flap effectiveness α/δ. Tests have generally been made of wings with propellers attached to them, so that the angle of attack of the wing in the jet was fixed, and only the flap angle was varied. As a result the flap effectiveness cannot be directly determined, but if theoretical values of C_{L_α} are assumed for the wing, it is possible to impute values of α/δ.

In the static case the jet deflection angle θ is a convenient measure of performance. It has been shown that the turning effectiveness θ/α of a wing is close to a limiting value for a wing of infinite chord when the chord is about equal to the jet height (fig. 7). This limiting value is plotted as a function of jet aspect ratio in figure 12. It is less than unity because of edge effects illustrated in figure 13. The absence of a pressure differential at the jet boundary causes an inward spanwise pressure gradient above the wing and an outward gradient below it, so that the streamlines in the cross plane converge above the wing and diverge below it. The average downwash is less than the downwash in the plane of the wing, and the jet deflection angle is therefore less than the wing angle of attack. As the jet width is increased, the edge effects become less important, and the maximum turning effectiveness θ/α for an infinitely wide jet is predicted to be unity in agreement with the Coanda effect. For a circular jet the limiting turning effectiveness of a wing of large chord is found by slender-body theory (ref. 3) to be

$$\theta/\alpha_{max} = 1 - (4/\pi^2) = 0.595$$

For a pair of propellers producing a wide slipstream figure 12 indicates that the limiting turning ratio should be about 0.73.

Figure 14 is taken from Kuhn's summary of the results of tests of propeller-wing-flap combinations (ref. 15). It shows the turning effectiveness of flaps measured in static tests as a function of flap chord. Figures 15 and 16 show the results of several series of tests in greater detail. It can be seen that for some flap configurations θ/δ has been measured to be as high as 0.75. If the theoretical maximum value of θ/α is substituted in the relation

$$\theta/\delta = (\theta/\alpha)(\alpha/\delta)$$

these results indicate values of α/δ close to or even greater than unity.

The value imputed by the theory to θ/α_{max} depends on the application of the boundary condition without regard for jet deflection and distortion. Nevertheless, the edge effects should prevent a jet from being deflected through the full wing angle of attack. Assuming, therefore, that the theory is not grossly underpredicting the turning effectiveness of a complete wing, it appears that the flap effectiveness must be substantially greater in a jet than in a free stream. In fact the result of slender-body theory that the trailing-edge deflection angle is equivalent to wing angle of attack may be close to the truth.

CONCLUSION

The methods described in this paper provide a basis for engineering calculations which show good correlation with published experimental data for wings without flaps. In the light of the theory the jet deflection angles measured in tests of flapped wings are surprisingly large. There is a need for tests in which the jet producing device is removed from the wing so that the effect of changing the wing and flap angles can be measured separately to give an exact value of flap effectiveness. It would also lead to a better insight into the problem if the final shape and location of the jet could be determined. If jet distortion and deflection have an important influence on the interaction, it would be possible to allow for their effect by representing the slipstream boundary by a freely convecting vortex layer, and using a direct numerical approach, but massive computations would be needed to carry it through.

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WING IN A WIDE SLIPSTREAM

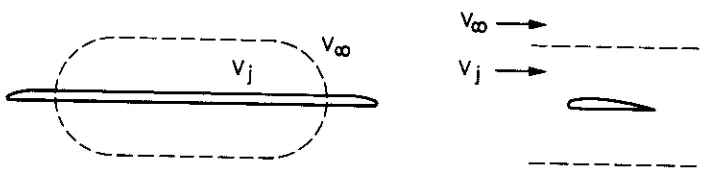


Figure 1

WING SPANNING A RECTANGULAR JET

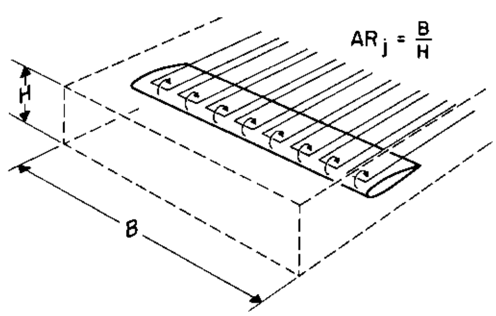


Figure 2

IMAGES FOR A HORSESHOE VORTEX

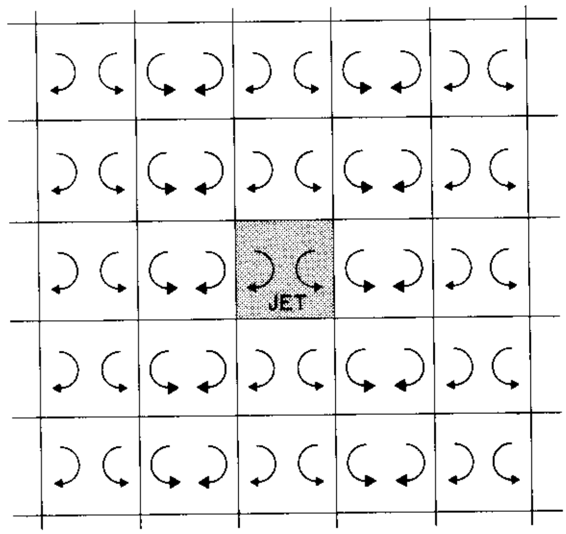


Figure 3

DECOMPOSITION OF A HORSESHOE VORTEX INTO TWO DIMENSIONAL AND ANTISYMMETRIC PARTS

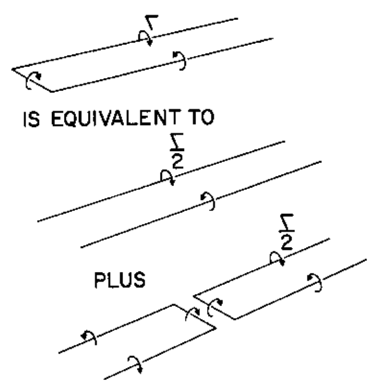


Figure 4

VORTEX PAIR IN AN ELLIPTIC SLIPSTREAM

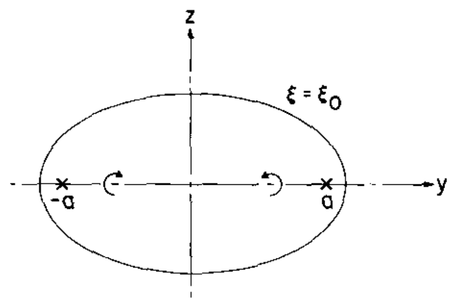


Figure 5

WING SPANNING FOCI OF ELLIPTIC SLIPSTREAM

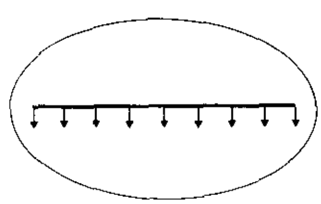


Figure 6

OPERATIONAL CURVES FOR A RECTANGULAR WING
AR = 2

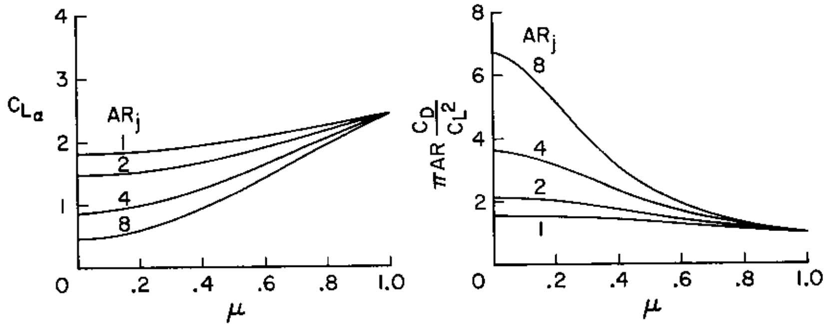


Figure 7(a)

OPERATIONAL CURVES FOR A RECTANGULAR WING
AR = 4

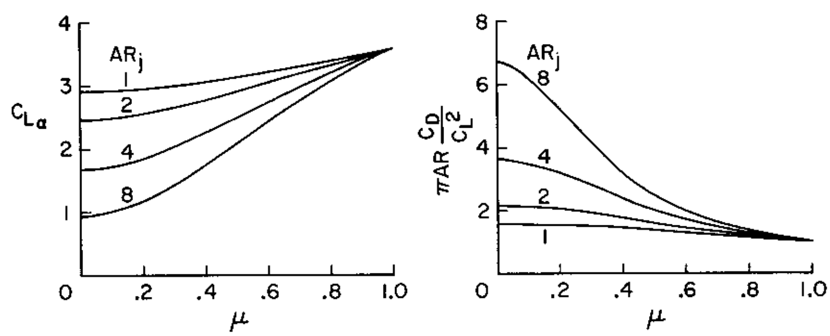


Figure 7(b)

TURNING EFFECTIVENESS OF RECTANGULAR WINGS IN STATIC JETS

$\mu = 0$

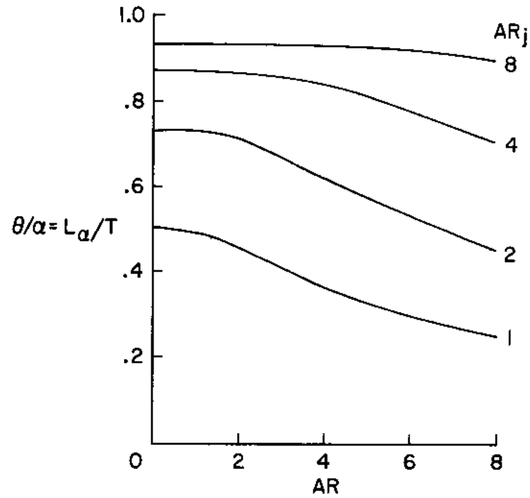


Figure 8

EFFECT OF DISPOSITION OF JETS ON THE STATIC TURNING EFFECTIVENESS OF A RECTANGULAR WING OF ASPECT RATIO 4

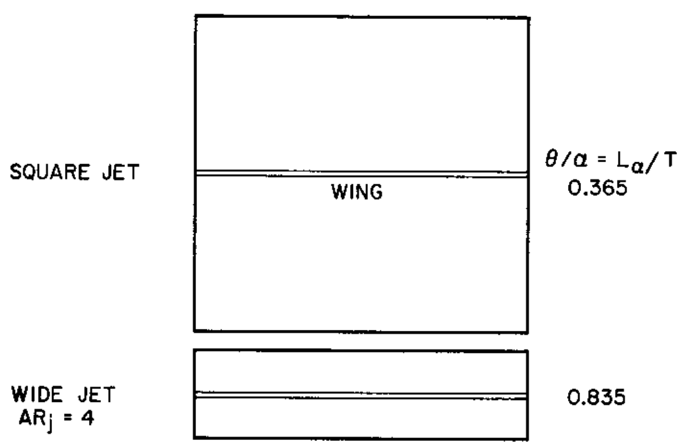


Figure 9

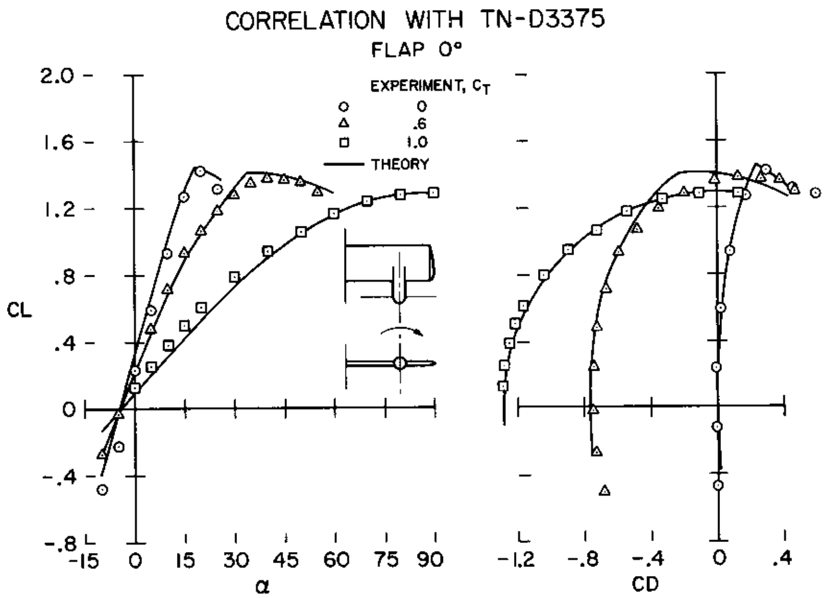


Figure 10

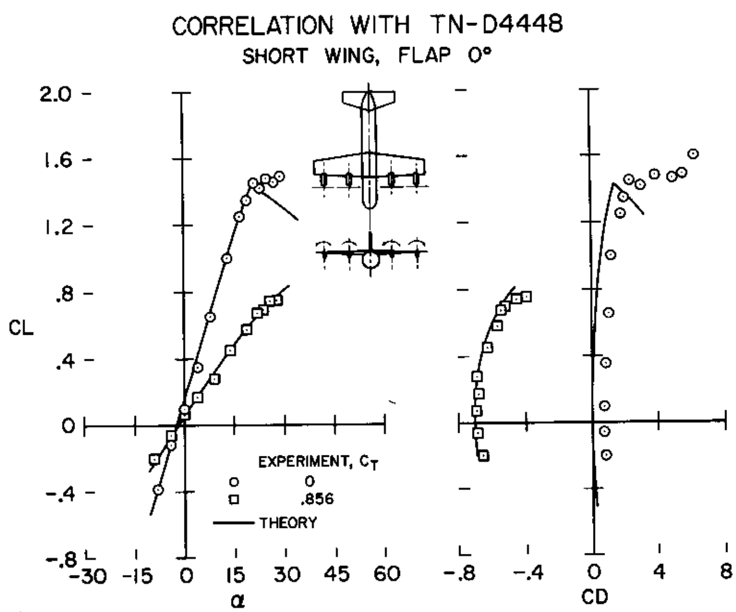


Figure 11

FLOW IN THE CROSS PLANE OF A JET
OVER A WING

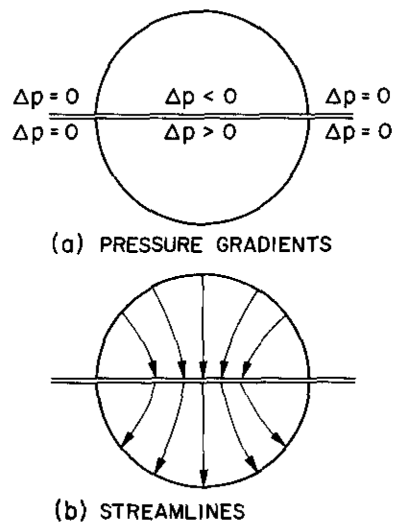


Figure 12

EFFECT OF JET WIDTH ON LIMITING
TURNING RATIO

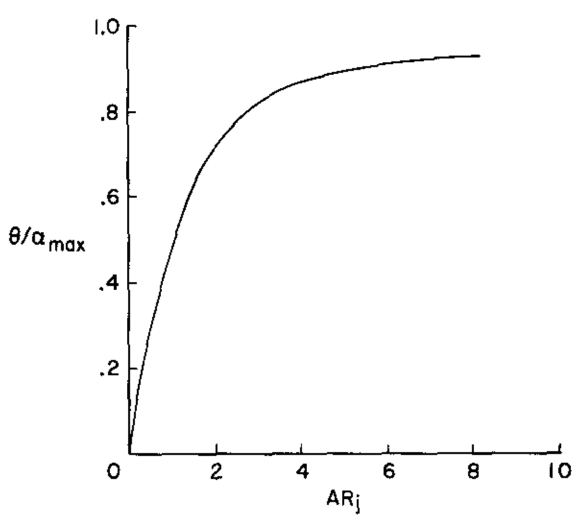


Figure 13

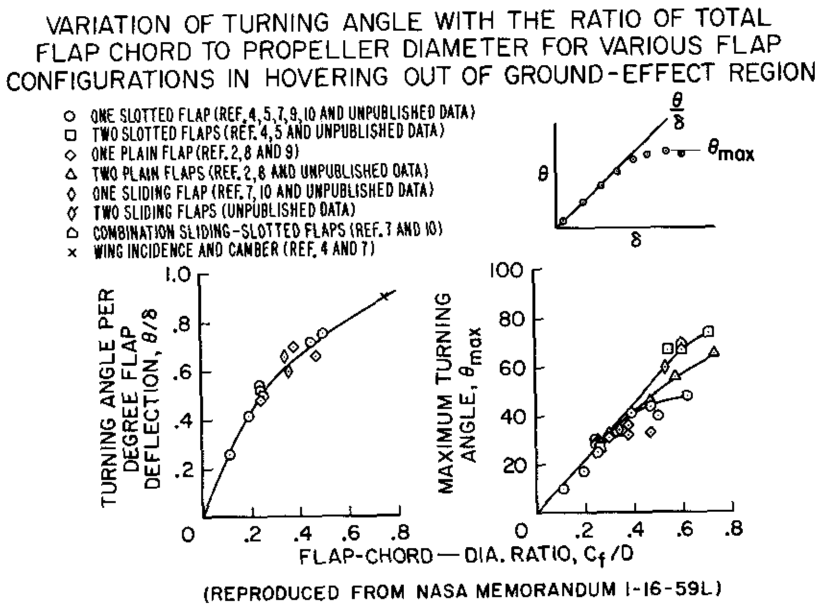


Figure 14

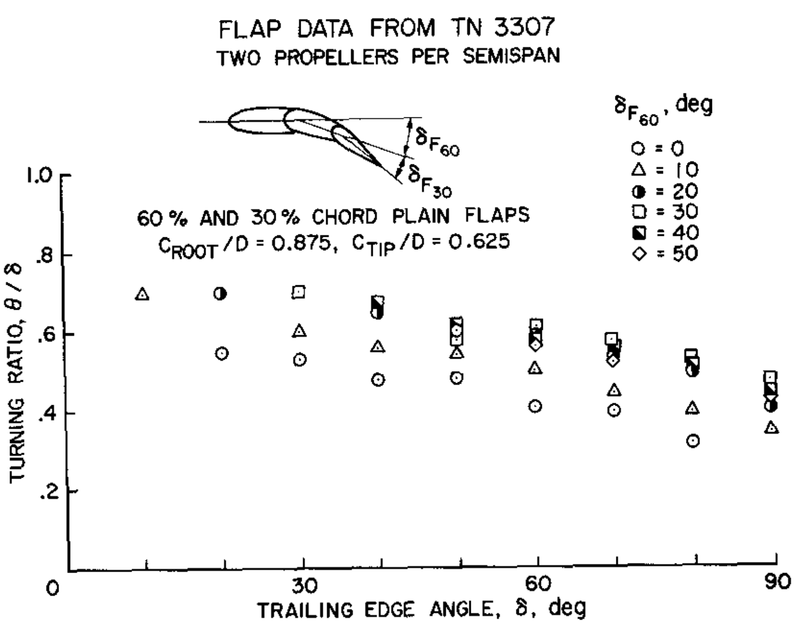
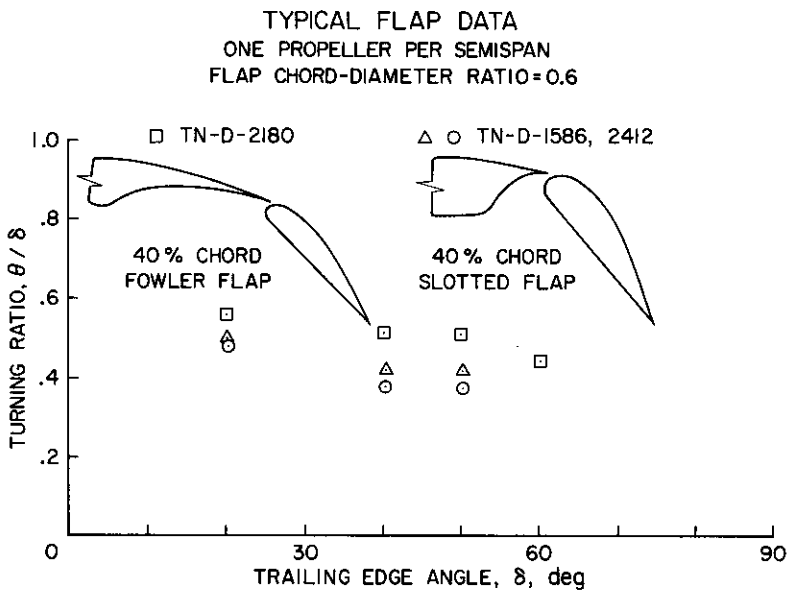


Figure 15



TYPICAL FLAP DATA
ONE PROPELLER PER SEMISPAN
FLAP CHORD-DIAMETER RATIO = 0.6
□ TN-D-2180
△ ○ TN-D-1586, 2412
40% CHORD
FOWLER FLAP
40% CHORD
SLOTTED FLAP
TURNING RATIO, θ / δ
1.0
.8
.6
.4
.2
0
30
60
90
TRAILING EDGE ANGLE, δ, deg

Figure 16

DISCUSSION

ELY S. LEVINSKY, Air Vehicle Corp.: Is the propeller slipstream tilted or untilted when the wing is tilted?

JAMESON: In the correlations I showed you, the propeller was fixed to the wing so they were tilted together. When there is a forward speed, of course, there would be some variation between the tilt of the slipstream and the wing, because of the interaction with the external flow, but statically the wing has a fixed angle of attack in the slipstream.

LEVINSKY: Well, at forward speed does the theory account for tilt of the propellers?

JAMESON: Well, this is one of the problems in the correlation. With this theory we are attempting to concentrate on the slipstream-wing interaction, but in order to correlate with available experiments, you are obliged to estimate the normal force of the propeller and the angle of the flow behind it. Therefore, when I showed you the correlation up there for that configuration, there was a procedure for estimating these. I would be happier to have tests in which you could separate all these factors. I think it would be easier to pin down whether you are really getting a good agreement or not.

LEVINSKY: I might mention that a while back Air Vehicle Corp. had done some work in this area under Army sponsorship. We treated the propeller-slipstream-wing interaction using essentially Ribner's method that you mentioned. Professor Hans Thomann, who participated in the program, developed an inclined actuator disk theory which was incorporated into the method so we could treat inclined propellers and wing angle of attack. We dealt with one, two and four propellers, but their slipstreams were separated, not merged, like you treated. Also, we included effects of slipstream rotation.

But I am in complete accord with you on the matter of test data. We got into the problem where we didn't really have adequate test data with which to evaluate the theory, and it was left at that. I might mention there are some very nice test data that were obtained by Stüper in Germany in 1938 (NACA TM-874). We have a hard time locating any better test data.

JAMESON: Yes, I agree with you completely. I think Stüper's tests are the sort of thing we would like to see renewed.

LEVINSKY: Because he did take out the swirl.

JAMESON: Yes, I know.

LEVINSKY: One further question. One of your slides showed a sharp corner on it, in the theory. This was when you looked at C_L versus α, and I was wondering . . .

JAMESON: Oh, yes, I am sorry about that. In the practical method - slide 12, please. I really ought to have deleted that. When dealing with this practical correlation, I introduced an allowance for stall angle which is empirical. That has really nothing to do with the theory, but in trying to carry large angles of attack, you may get the wing outside the slipstream stalled and the wing inside the slipstream not stalled, so in order to carry it through, you've got to do something about estimating the stall. But that is not a theoretical stall estimate.

DAVID BEVAN, Boeing Company, Vertol Div.: First of all, let me say that you seem to have done very well with a very difficult subject, and after looking at perhaps 14 years of wind-tunnel data from Langley, we at Boeing do some computer work, but we have also spent something like 1,400 hours of wind tunnel time on this problem this past year, and we are looking forward to following your results.

It is very difficult to handle the stall problem, which you have drawn empirically there. As the man from Air Vehicle Corporation said, a propeller alone is very difficult to calculate and is often calculated wrong. It isn't that the force contribution is a very large part of the lift; it is that it suppresses the leading-edge angle of attack.

JAMESON: Yes, exactly.

BEVAN: And between that and the upgoing and outgoing size of the props, you've got a very difficult wing loading distribution problem. So you certainly are embarked on a very difficult course.

JAMESON: Yes. I would like to have a simple test of a wing in two flows and see if we can agree with that as a first step.

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