N78-24052

COMPARISON OF AERODYNAMIC THEORY AND EXPERIMENT FOR JET-FLAP WINGS

Thomas G. Gainer, Long P. Yip, and Raymond D. Vogler
NASA Langley Research Center

SUMMARY

This paper compares aerodynamic theory predictions made for a jet-flapped wing with experimental data obtained in a fairly extensive series of tests in the Langley V/STOL tunnel. The predictions were made with the EVD (Elementary Vortex Distribution) program developed by Lopez, Shen, and Wasson at McDonnell-Douglas. The tests were made on a straight, rectangular wing and investigated two types of jet flap concepts: a pure jet flap with high jet deflection and a wing with blowing at the knee of a plain trailing-edge flap. The tests investigated full- and partial-span blowing for wing aspect ratios of 8.0 and 5.5 and momentum coefficients from 0 to about 4.

The total lift, drag, and pitching-moment coefficients predicted by the theory were in excellent agreement with experimental values for the pure jet flap, even with the high jet deflection. The pressure coefficients on the wing, and hence the circulation lift coefficients, were underpredicted, however, because of the linearizing assumptions of the planar theory. The lift, drag, and pitching-moment coefficients, as well as pressure coefficients, were underpredicted for the wing with blowing over the flap because of the failure of the theory to account for the interaction effect of the high velocity jet passing over the flap.

INTRODUCTION

Jet-flap theory is a relatively simple powered-lift theory developed by assuming that the jet exhaust that augments lift leaves the wing trailing edge at small angles as a thin sheet. The theory was first developed in two dimensions by Spence (ref. 1), then in three dimensions by Maskell and Spence and others. (See ref. 2.) More recently, lifting-surface programs patterned after those for conventional wings have been developed that can predict chordwise and spanwise loadings for complex wing planforms and arbitrary distributions of momentum coefficient and jet deflection. These programs include the EVD (Elementary Vortex Distribution) program (ref. 3) and the Vortex-Lattice Program for Jet-Flapped Wings (ref. 4).

Although the basic assumptions somewhat restrict the theory, it could have important applications. Designers are examining the jet-flap concept, for example, in connection with the two-dimensional nozzles being considered for

102 PAGE INTENTIONALLY BLANK

advanced supersonic aircraft. These nozzles would be mounted at the trailing edge of the wing and could be deflected to provide lift augmentation - either to improve performance or, in the case of fighters, to improve maneuvering; since these nozzles spread the exhaust into a fairly thin sheet, jet-flap theory would apply in their design. For many STOL applications, flow conditions may be outside the strict limitations of the theory; nevertheless, there are indications jet-flap theory could be used. Although the theory is based on small-disturbance concepts, the theory predictions have agreed for some cases with test data at high deflections. Jet-flap theories have also predicted aerodynamic characteristics of other configurations such as the augmentor wing and the externally blown flap (ref. 5).

The different applications of the theory have not been examined in detail, however, nor have the theories themselves been verified to any great extent because the necessary experimental data have not been available. For most of the powered-lift data available, the distributions of momentum coefficient and jet-deflection angle are not defined well enough to use in theory predictions. The data that have these distributions defined are limited to just a few blowing spans and jet deflections. Detailed pressure distributions are not generally available for comparison with theoretical predictions.

To provide some of the necessary data, Langley Research Center conducted a series of wind-tunnel tests that investigated a fairly wide range of jet-flap parameters. This paper compares predictions made with a representative jet-flap theory, namely the EVD theory (ref. 3) with these experimental data. The test model had a straight, untapered wing. It was tested with two powered-lift configurations which, while they do not quite agree with the assumptions of the theory, would be of interest in STOL applications. In one configuration the wing was equipped with a pure jet flap with high jet deflection, whereas in the other, the wing was equipped with blowing over a plain trailing-edge flap. Partial- and full-span blowing and two wing aspect ratios (8.0 and 5.5) were investigated. The model was tested through an angle-of-attack range from about -4° to 20° at momentum coefficients from 0 to about 4.

SYMBOLS

A aspect ratio

a_{ij} influence coefficient relating vorticity at a point j to downwash at a point i

b span

C_D net drag coefficient, based on model drag minus component of model thrust in drag direction

C_L lift coefficient

$C_{L,jr}$ jet-reaction lift coefficient

C_{L_Γ}	circulation lift coefficient
C_m	pitching-moment coefficient (referred to the wing apex)
C_μ	jet-momentum coefficient
c	wing chord
c_p	section pressure coefficient
Δc_p	difference between upper and lower surface pressures
c_μ	section jet-momentum coefficient
F_A	axial force
F_N	normal force
K	constant in thickness correction factor
k	thickness correction factor
S	wing area, m^2 (ft^2)
S_b	blown area of wing (blown span times wing chord), m^2 (ft^2)
t/c	wing thickness-chord ratio
T	thrust
w_i	induced downwash at a control point i
x	chordwise distance
y	spanwise distance
α	angle of attack, deg
γ	vorticity
δ_f	flap deflection, deg
δ_j	jet turning angle, deg
η	thrust efficiency factor; actual thrust divided by nominal calibrated thrust

MODEL AND APPARATUS

The test model is shown in the Langley V/STOL tunnel in figure 1. The fuselage was designed small enough to have negligible effect on the wing aerodynamic characteristics, yet large enough to contain the model balance, pressure gages, and associated tubing required in the tests.

Figure 2 shows some of the wing details. The wing had a 25.4-cm (10 in.) chord and an NACA 0018-64 airfoil section. It was tested as an aspect-ratio-8.0 wing (2.03-m (80 in.) span) with blowing over the full span, two-thirds of the span, or one-third of the span; then the outboard one-third of the wing was removed and it was tested as an aspect-ratio-5.5 wing (1.02-m (40 in.) span) with full- or half-span blowing. The leading-edge slat shown was used to prevent separation at the leading edge at high angles of attack and high jet deflections. Air for blowing was provided by the tunnel high-pressure air supply which was brought in through the sting.

For the pure jet flap (fig. 2), the wing remained in its basic airfoil shape, with the trailing edge undeflected, and air was ejected from a slot on the lower surface at the trailing edge. The air was ejected at an angle of approximately 60° with respect to the wing chord line.

For blowing over the flap (fig. 2), the part of the wing containing the jet flap was removed and replaced with a 25-percent-chord deflectable plain flap. A "slot" at the knee of the flap, consisting of 300 holes 0.159 cm (0.063 in.) in diameter and equally spaced along the span, provided the air for blowing. The flap was divided into three spanwise segments for different amounts of partial-span blowing, and only the flap segment along the blowing span was deflected. For example, with 1/3-span blowing, only the inboard 1/3-flap segment was deflected and the remaining two outboard segments were undeflected. Flap deflections of 0°, 15°, 30°, 45°, and 60° were investigated.

Model forces and moments were measured with a six-component strain-gage balance. Static pressures were measured at six spanwise stations on the right wing panel $\left(\frac{y}{b/2} = 0.15, 0.30, 0.45, 0.60, 0.78, \text{and } 0.93\right)$ and, as a check on symmetry, at one station $\left(\frac{y}{b/2} = 0.30\right)$ on the left panel. There were 31 orifices on the wing at each station - 19 on the upper surface and 12 on the lower surface.

THEORETICAL CALCULATIONS

The theoretical calculations were made with the Elementary Vortex Distribution (EVD) program described in reference 3. The EVD program is a lifting-surface program that represents the wing and jet wake with a vortex sheet of varying intensity. The vortex strength on the wing is determined by satisfying the tangent flow boundary condition on the wing. This is done by setting the sum of the induced velocities w_i (fig. 3) equal to the components of free-stream velocity normal to the wing surface so there can be no flow through the wing surface. The vorticity along the jet wake is determined by using the basic Spence relationship that expresses vorticity in terms of section momentum coefficient and the change in induced downwash with respect to downstream distance as follows:

$$\gamma_i = - \frac{cC_\mu}{2} \frac{\partial w_i}{\partial x}$$

The program has been linearized by assuming small perturbations and that all vorticity lies in the plane of the wing. The boundary conditions have been projected back to the plane of the wing. The camber, twist, and jet-deflection angles are assumed to be small.

The EVD program adds a degree of sophistication to the basic vortex scheme by assuming a continuously varying chordwise vorticity constructed from different types of basic vortex elements. The EVD uses overlapping triangular elements to obtain a linearly varying vorticity between two points on the wing, a square-root singularity at the leading edge, and logarithmic singularities at the flap hinge line and at the trailing edge where the jet exits from the wing. An "infinity" EVD, for which the vorticity goes to zero as one over the square of downstream distance, is used to represent the trailing jet sheet far downstream.

The EVD program accounts for wing camber and twist and allows for a trailing-edge flap, but the assumption is made that the jet is emerging from the trailing edge of the flap, not from a point on the upper surface of the wing. The program assumes a thin wing; however, thickness effects can be accounted for by multiplying circulation lift and wing pressure coefficients by the following correction factor:

$$k = 1 + K \frac{S_b}{S} \frac{t}{c}$$

where the constant K is usually taken to be 0.8 for airfoils with sharp trailing edges and 1.0 for cusped airfoils. The correction factors used varied from 1.144 with full-span blowing to 1.048 with 1/3-span blowing.

In making the EVD calculations, EVD elements were placed at 20 spanwise stations along the semispan for the aspect-ratio-8 wing and at 16 spanwise stations for the aspect-ratio-5.5 wing. There were six chordwise elements on the wing and five on the jet.

The momentum coefficient and jet-deflection angles needed to make the calculations were determined by static calibration, as shown in figure 4. For the blown-flap wing, a nominal thrust was first determined by calibrating the thrust at the blowing slot with the flap off. Then, with the flap on, force components were measured normal to and along the wing chord line and resolved into a resultant force. An efficiency factor η, which is the ratio of the actual or resultant thrust to the nominal thrust, was then determined, as was the jet deflection or turning angle δ_j, which is the angle between the resultant thrust and the wing chordline. The wing with blowing over the flap had efficiencies varying from about 0.85 at $\delta_f = 0^o$ to between 0.75 and 0.79 at $\delta_f = 60^o$. The turning angle with blowing over the flap was about equal to the angle of the flap upper-surface deflection $(\delta_f + 13.5^o)$. The pure jet flap was calibrated the same way as the blown flap, except that it was calibrated with the jet flap in place so that the nominal thrust was equal to actual thrust and its efficiency factor was 1.0. The static results show that the jet-deflection angle for the pure jet flap was between 61° and 63°. In the calculations, the momentum coefficient and jet-deflection angles were assumed to be uniformly distributed over the blowing span.

RESULTS AND DISCUSSION

Pure Jet Flap

Comparison of total lift, drag, and pitching moment.- The lift, drag, and pitching-moment comparisons shown in figures 5, 6, and 7 indicate excellent agreement between theory and experiment for the pure-jet-flap wing. The results for full-span blowing with the aspect-ratio-8 wing $(\delta_j = 61.4^o)$ are given in figure 5; the results with 1/3- and 2/3-span blowing for this wing are given in figures 6 and 7, respectively. Except at $C_\mu = 0$, the theoretical predictions generally agreed closely with experiment through the C_μ range for the three blowing spans.

The poor agreement at $C_\mu = 0$ was caused by the fact that there was a good deal of separated flow on the wing without blowing. The leading-edge slat interfered with the flow at low angles of attack, and the flow was separated around the trailing edge at all angles of attack because the airfoil was relatively thick (t/c = 0.18). Just a moderate amount of blowing cleaned up the separated flow so that the theory was brought into close agreement with the experimental data.

The theory slightly underpredicted the lift at $C_\mu = 3.9$, but this disagreement between theory and experiment was not typical; data for other configurations showed good agreement at high C_μ. The fact that the agreement was as good as it was validates the thickness correction that was applied to the lift coefficients estimated by the thin-wing theory. Without this correction, the predicted lift coefficients would be noticeably lower than experiment throughout the C_μ range.

The drag coefficients shown are based on the net force in the drag direction measured by the model balance and, therefore, include the model thrust. The profile drag coefficient of the model (the value where the $C_\mu = 0$ curve intersects the $C_L = 0$ axis) was about 0.07, which was very small compared with the overall level of drag being measured. Most of the drag developed was induced drag, and the results indicate the theory was able to predict the induced drag very accurately. The fact that the theory assumed 100-percent suction and gave good drag prediction indicates that the wing was experiencing full thrust recovery. Results for the aspect-ratio-5.5 wing are not presented, but there was excellent agreement between theory and experiment for this wing also.

Comparison of force components.- The fact that the theory gave good predictions of total force and moment coefficients at the high jet deflection, even though it has been linearized and assumes small jet-deflection angles, is consistent with some of the previous results for the jet flap, which also show good agreement with test data at high jet deflections. (See, for example, Spence's two-dimensional comparisons in reference 1 and also comparisons for an augmentor wing in reference 5.) This good agreement can be explained by examining the components of the forces and moments. It can be shown that while the predicted total forces and moments agreed with experiment, the components of the forces and moments did not agree. The following table compares the theoretical and experimental components of lift coefficient for the 2/3-span blowing case at a C_μ of 3.9 $(\eta C_\mu = 3.6)$ and $\alpha = 0^o$. The components shown (for no flap deflection and $\alpha = 0^o$) are the jet-reaction lift coefficient $C_{L,jr}$, which is the lift coefficient due to the thrust acting at the trailing edge, and the circulation lift coefficient $C_{L\Gamma}$, which is the lift coefficient obtained by integrating the pressure distributions on the wing.

	$C_{L\Gamma}$	$C_{L,jr}$	C_L
Planar theory	2.32	3.88	6.20
Experiment	3.15	3.17	6.32

Whereas the total lift coefficients agree within about 2 percent, the small-angle theory overestimates the jet-reaction lift coefficient: the small-angle value for $C_{L,jr}$ is $\eta C_\mu \delta_j$ $(\delta_j$ in radians$)$, whereas the true jet-reaction lift coefficient is $\eta C_\mu \sin \delta_j$. The planar theory, on the other hand, will underestimate the circulation lift, and hence, the pressure distribution on the wing.

Comparison of pressure distributions.- The pressure distributions in figure 8 show the extent to which the linear theory underestimates the pressures on the wing, and hence, the circulation lift developed. Pressure distributions in figure 8 are for the pure-jet-flap wing with 2/3-span blowing at a C_μ of 3.9. The plots shown give the net pressure difference Δc_p between the upper and lower surfaces as a function of nondimensional chordwise distance along the wing. (In the EVD calculations $\Delta c_p = 2\gamma$, where γ is the vorticity at a given point.) The theoretical pressure distributions shown have been corrected for wing thickness effects. The pressure distributions are given for three spanwise stations; the two inboard stations have blowing, the one outboard station has no blowing. It is seen that the theory underpredicts the pressures at the two inboard stations for which there is blowing $\left(\frac{y}{b/2} = 0.15 \text{ and } 0.45\right)$ but is in good agreement with experiment at the outboard station $\left(\frac{y}{b/2} = 0.78\right)$ where there is no blowing.

The lower wing pressures predicted by the theory can be attributed to the high jet deflections involved and to the fact that the theory satisfies boundary conditions in the plane of the wing rather than on the jet wake (see fig. 3). The effect of these planar assumptions is demonstrated by the results of a two-dimensional study in figure 9. Figure 9 shows pressure distributions calculated with a program developed by Clever (ref. 6) for a flat-plate two-dimensional wing with $C_\mu = 3.5$ and $\alpha = 0^\circ$. The nonplanar theory was developed without making linearizing assumptions; the planar theory assumes small angles and that vorticity lies in the plane of the wing. The comparisons show that at $\delta_j = 10^\circ$, there is no difference between the nonplanar and planar theories; at $\delta_j = 30^\circ$, which is about the limit of the small-angle assumptions, small differences start to appear. At $\delta_j = 60^\circ$, the linearized planar theory gives lower pressures than the nonplanar theory, particularly close to the wing trailing edge.

At both $\delta_j = 10^\circ$ and $\delta_j = 30^\circ$, the total as well as the components of lift coefficient were about the same for the nonplanar and planar theories. The table in figure 9 compares these lift coefficients at $\delta_j = 60^\circ$ and shows that, as was the case for the three-dimensional planar theory and experiment, total lift coefficient was about the same for the planar and nonplanar theories, even though the components did not agree. The planar theory overestimated the jet-reaction lift, but compensated for it by underestimating the circulation lift by about the same amount.

Wing With Blowing Over the Flap

Comparison of total lift, drag, and pitching moment.- Lift, drag, and pitching moments for the wing with blowing over the trailing-edge flap are shown in figure 10. The results are for the aspect-ratio-8 wing, full-span blowing, and $\delta_f = 30^\circ$. They are typical of those for all blown-flap configurations in that they show the theory consistently underestimated the lift and pitching moments for this wing throughout the C_μ range. The predicted lift-drag curves were in good agreement with experiment, but the drag at a given angle of attack was substantially lower for the theory than for experiment.

These results indicate there is a substantial interaction effect due to the jet exhaust passing over the flap that was not accounted for in the theory, which assumes the jet exhaust emerges from the trailing edge of the wing. This is substantiated by the pressure distributions for the blown-flap wing as described in the following section.

Comparison of pressure distributions.- Figure 11 shows the pressure distributions for the blown-flap wing for two flap deflections, 30° and 0°. These distributions, given at the 15-percent-semispan station, show both upper and lower surface pressures. These were obtained by solving the thickness problem for upper and lower surface velocities with no blowing, then adding these to the velocities determined for the thin wing with blowing from the EVD program. The velocities were then converted into pressure coefficients by using the incompressible Bernoulli equation.

The pressure distribution for $\delta_f = 30^\circ$ indicates a high negative pressure peak around the flap hinge line and jet slot location (at 0.75c); the theoretical pressure distribution also has a negative pressure peak at this location because the flap is deflected. The pressures given by the theory around the hinge line, however, seem to be much lower than the experimental values, indicating that the high-velocity jet emerging from the slot also has a substantial effect. The effect of the jet is even more apparent at $\delta_f = 0^\circ$. The experimental data for $\delta_f = 0^\circ$ again indicates a very high negative pressure around the jet slot and hinge location; however, the theoretical distribution indicates no such peak because the flap is undeflected. The theory, in this case, treats the wing as though it were a pure jet flap with a jet deflection equal to the angle of the upper surface of the flap.

The fact that the effect of the jet appears as a singularity that is similar to logarithmic singularity caused by flap deflection indicates that it might be possible to modify this singularity to account for C_μ effects as well as flap effects. If this cannot be done, then a more general wing-jet interaction program (similar to ref. 7) would be needed to account for the jet flow over the flap.

CONCLUSIONS

Comparisons made between theory and experiment for a straight, untapered wing with two types of powered lift (a pure jet flap and blowing over the flap) indicated the following conclusions:

1. The lift, drag, and pitching-moment coefficients predicted by the linearized planar theory were in excellent agreement with the experimental values for the pure jet flap, even though the jet deflection was large (61° to 63°).

2. The planar theory underpredicted the pressure coefficients and hence the wing circulation lift. The lower circulation lift was compensated for by a higher jet-reaction lift, under the small-angle assumptions, so that total lift and pitching moments were close to the correct values.

3. The lift, drag, and pitching-moment coefficients as well as pressure coefficients at a given angle of attack were underpredicted for the wing with blowing over the flap because of the failure of the theory to account for the interaction effect of the high-velocity jet passing over the flap.

REFERENCES

1. Spence, D. A.: The Lift Coefficient of a Thin, Jet-Flapped Wing. Proc. Roy. Soc. (London), ser. A, vol. 238, no. 1212, Dec. 4, 1956, pp. 46-68.

2. Margason, Richard J.; Yip, Long P.; and Gainer, Thomas G.: Recent Developments in Propulsive-Lift Aerodynamic Theory. Aerodynamic Analyses Requiring Advanced Computers, Part II, NASA SP-347, 1975, pp. 871-895.

3. Lopez, Michael L.; Shen, Cheng-Chung; and Wasson, Norman F.: A Theoretical Method for Calculating the Aerodynamic Characteristics of Arbitrary Jet-Flapped Wings. Rep. No. MDC J5519 (Contract N00014-71-C-0250), McDonnell Douglas Corp., May 1973.

   Volume I - The Elementary Vortex Distribution Jet-Wing Lifting Surface Theory.

   Volume II - EVD Jet-Wing Computer Program User's Manual.

4. Clever, W. C.: A Vortex Lattice Program for Jet Flapped Airfoils. TFD-73-70, Los Angeles Div., North American Rockwell Corp., Jan. 26, 1973.

5. Lopez, M. L.; and Shen, C. C.: Recent Developments in Jet Flap Theory and Its Application to STOL Aerodynamic Analysis. AIAA Paper No. 71-578, June 1971.

6. Clever, W.: Linear and Nonlinear Two Dimensional Jet Flap Analysis. TFD-72-698, Los Angeles Div., North American Rockwell Corp., Nov. 22, 1972.

7. Lan, C. Edward; and Campbell, James F.: Theoretical Aerodynamics of Upper-Surface-Blowing Jet-Wing Interaction. NASA TN D-7936, 1975.

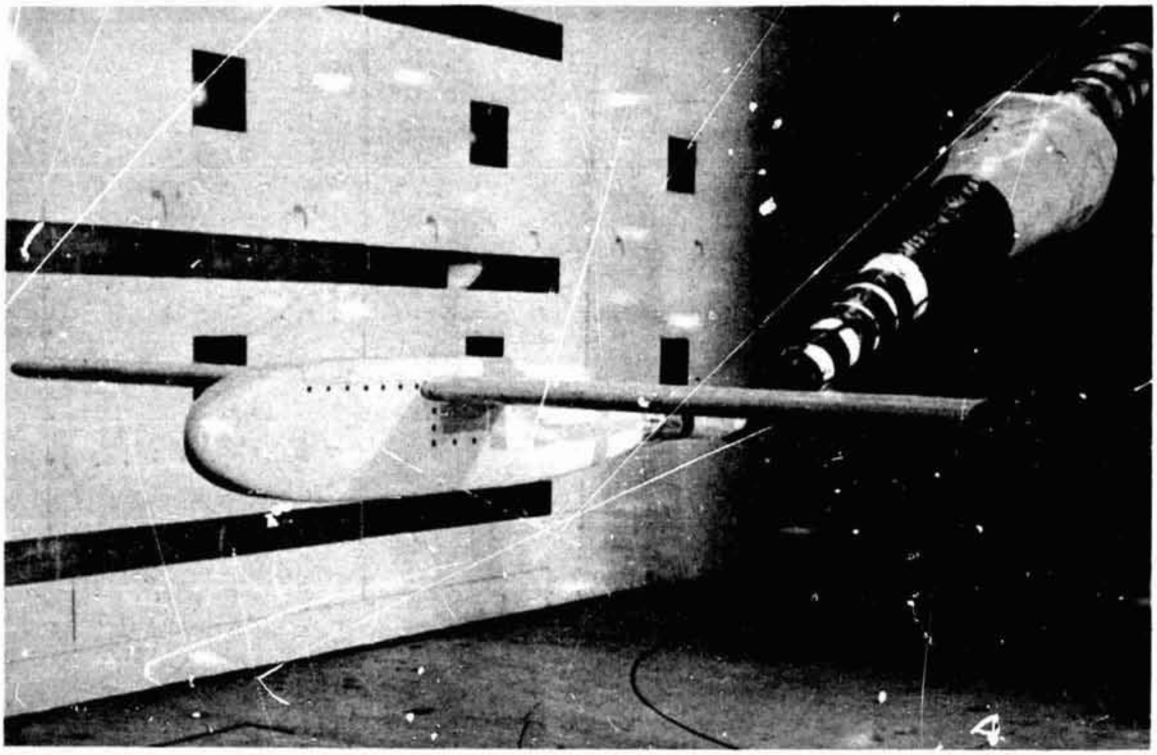


Figure 1.- Test model in the V/STOL tunnel.

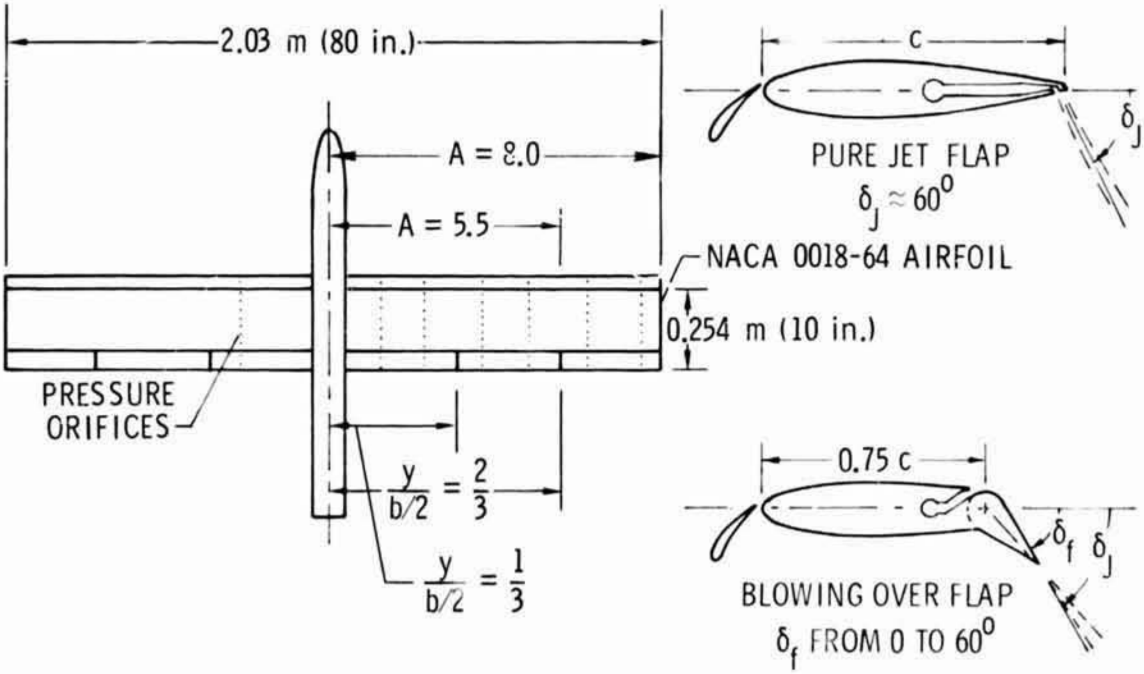


Figure 2.- Model details.

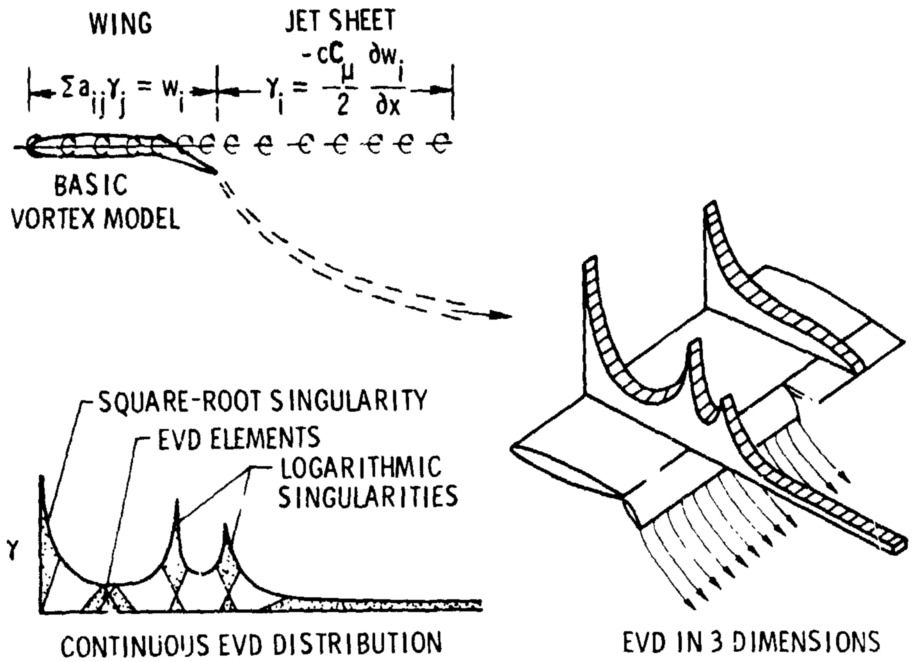


Figure 3.- Jet-flap lifting-surface theory.

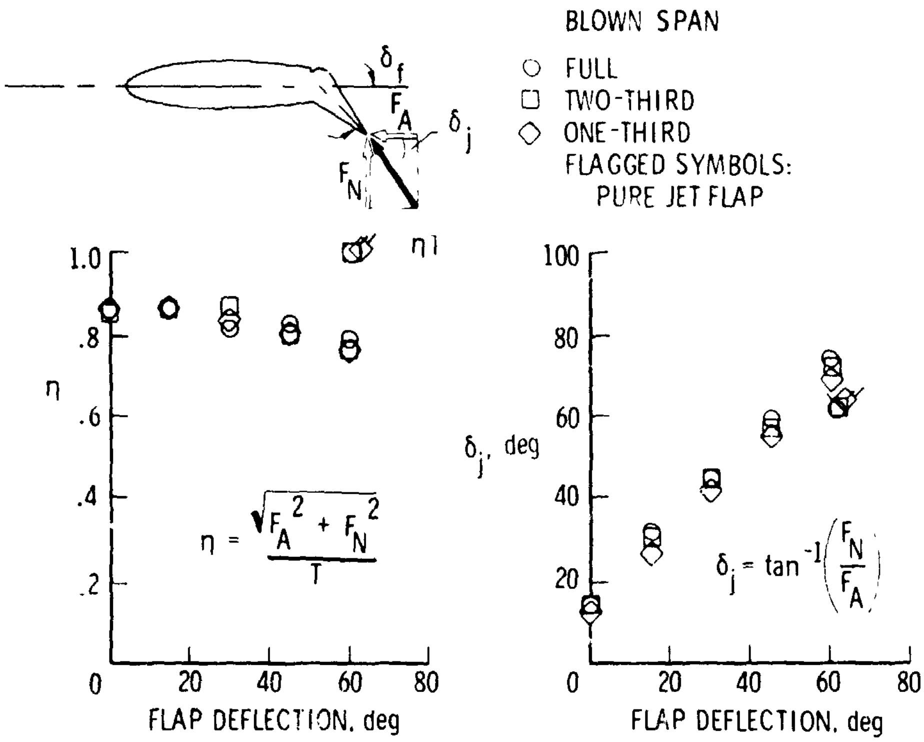


Figure 4.- Static turning characteristics.

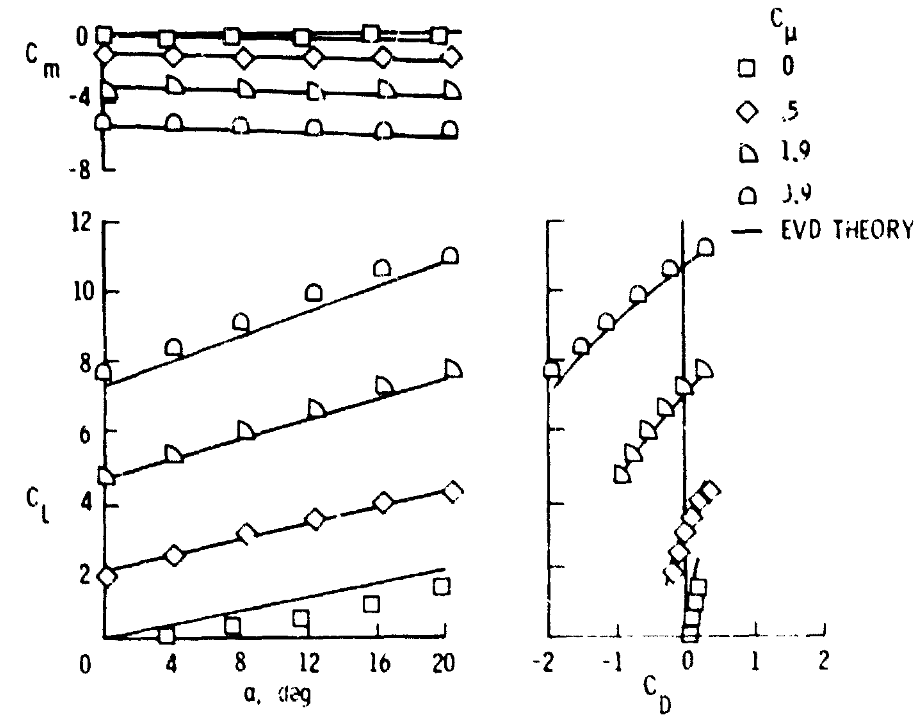


Figure 5.- Theory and experiment comparison for pure jet flap; A = 8; full-span blowing; $\delta_j = 61.4^o$.

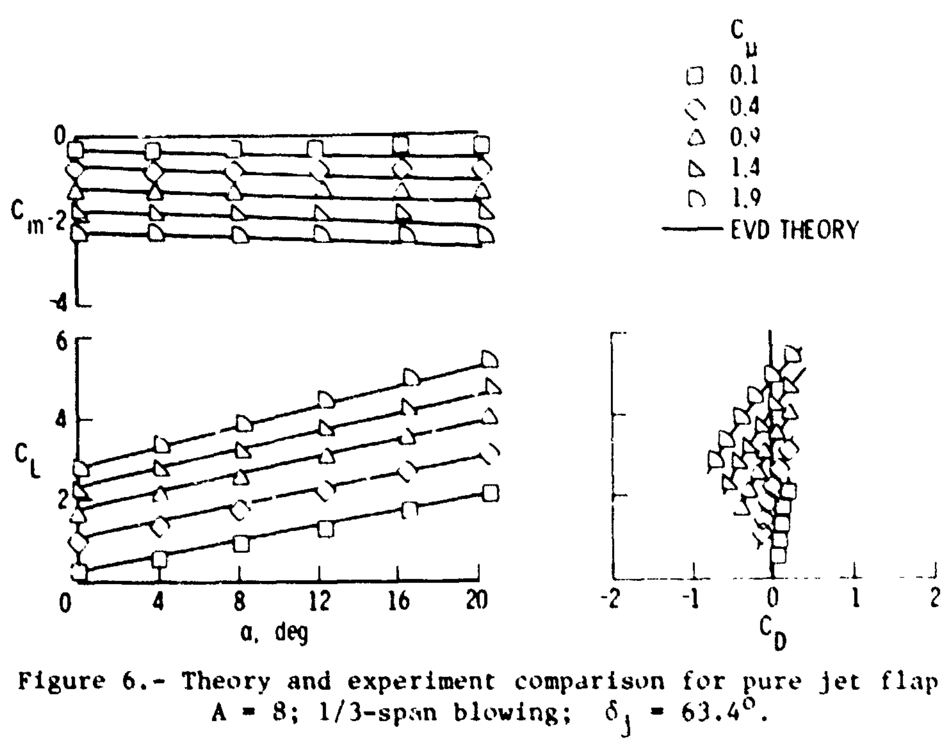


Figure 6.- Theory and experiment comparison for pure jet flap; A = 8; 1/3-span blowing; $\delta_j = 63.4^o$.

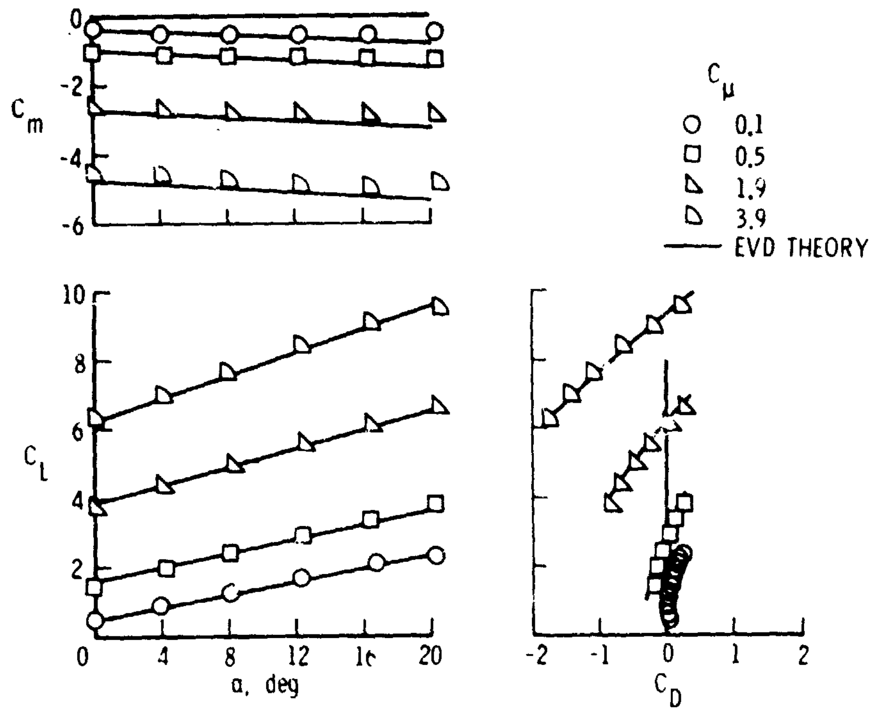


Figure 7.- Theory and experiment comparison for pure jet flap; A = 8; 2/3-span blowing; δ_j = 61.8°.

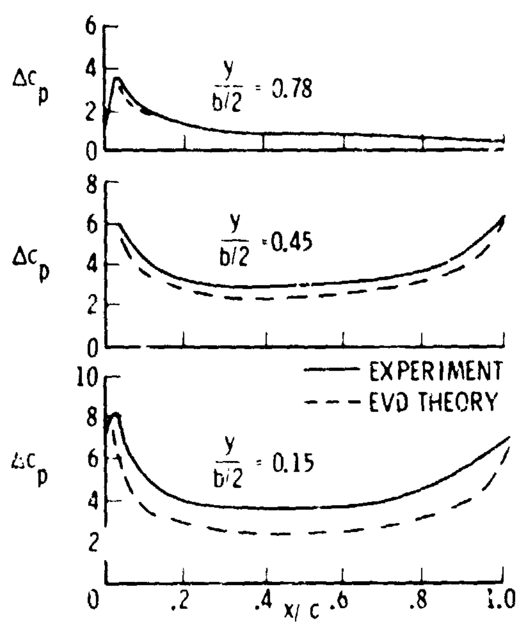
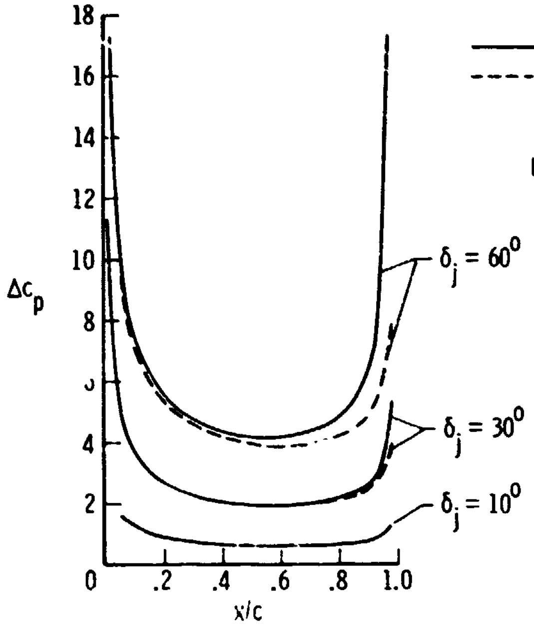


Figure 8.- Theoretical and experimental pressure distributions for pure jet flap. 2/3-span blowing; C_μ = 3.9.



LIFT COEFFICIENTS FOR $\delta_j = 60°$

THEORY	C_{L_Γ}	$C_{L,jr}$	C_L
NONPLANAR	6.19	3.03	9.22
PLANAR	5.43	3.67	9.10

Figure 9.- Effect of planar assumptions in two dimensions (ref. 6). C_μ = 3.5; α = 0°.

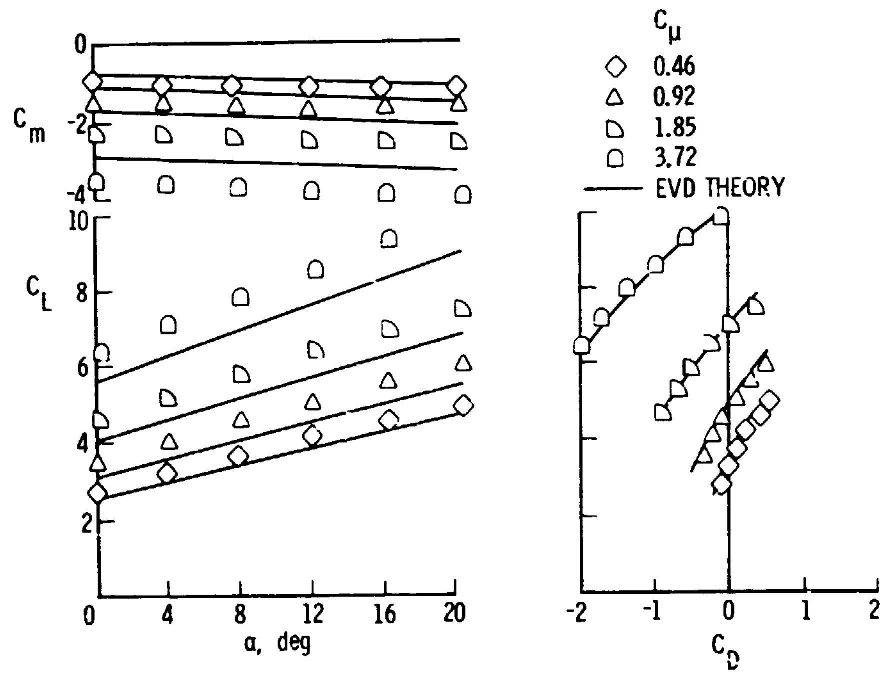


Figure 10.- Theory and experiment comparison for wing with blowing over flap A = 8.0; full-span blowing; δ_f = 30°.

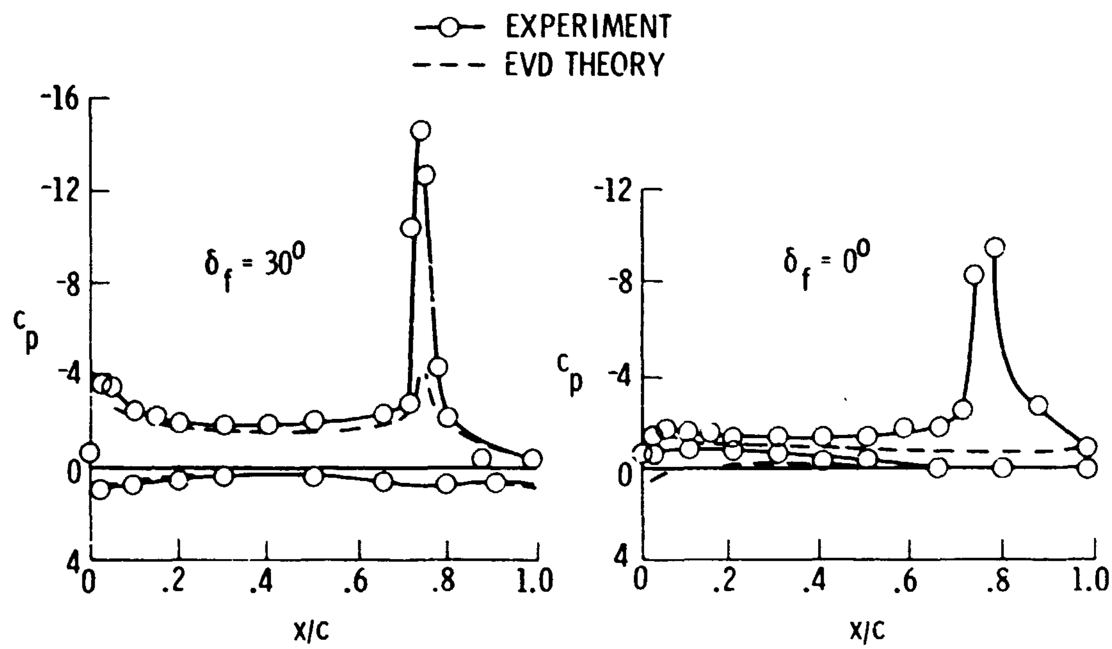


Figure 11.- Pressure distributions for wing with blowing over flap. 15-percent semispan station; $C_\mu = 3.9$.