21

21. EXPERIMENTAL AND THEORETICAL STUDIES OF WING-LEADING-EDGE VORTEX FLOW

By Mark W. Kelly, Victor R. Corsiglia,
and David G. Koenig
NASA Ames Research Center

SUMMARY

This paper presents a review of experimental and theoretical studies of leading-edge vortex flow on low-aspect-ratio wings. The experimental results show that such flow significantly increases lift-curve slope, reduces drag due to lift, and reduces static longitudinal stability at high values of lift coefficient. These results also show that the magnitude of these effects is increased by the use of wing planforms having high sweepback over the inboard portion of the wing.

Flow visualization studies of a low-aspect-ratio wing with the leading-edge swept 77° on the inboard portion of the wing and 59° on the outboard portion revealed the existence of two strong vortex cores. One of these originated at the intersection of the wing leading edge with the fuselage. The other originated in the vicinity of the discontinuity of leading-edge sweep angle. These two vortices interacted to produce a nonconical flow over the aft portion of the wing.

A brief review is presented of some of the existing theoretical methods for predicting the effects of vortex flow on the aerodynamic characteristics of wings. Two main deficiencies of these theoretical methods are that they do not allow for vortex interaction and that they are restricted to conical flows. A new theoretical approach which eliminates these deficiencies is described, and preliminary results obtained from this theory are compared with those obtained from other theories and with experimental results. This comparison indicates that the new theory holds promise for predicting the effects of vortex flow on low-aspect-ratio wings. However, additional work is required on the key problem of establishing the strength of the vorticity shed from the wing as a function of wing geometry and angle of attack.

INTRODUCTION

The subject of vortex flow on low-aspect-ratio wings has challenged researchers in aerodynamics for many years. For example, in 1939 Bollay presented a theoretical study of vortex flow on low-aspect-ratio rectangular wings (ref. 1). This was followed more recently by theoretical studies of vortex flow on triangular wings (e.g., refs. 2 and 3) and by many experimental studies (e.g., ref. 4). However, vortex flow still is not sufficiently well understood to allow reliable quantitative predictions of its effects on aerodynamic characteristics for use in wing design. In addition, many wing

Preceding page blank

planforms of current interest, such as double-delta and variable-sweep wings, show strong effects of vortex flow. Therefore, additional studies are of interest and are required.

The type of vortex flow to be considered in this paper is illustrated on figure 1 for both a variable-sweep wing and a low-aspect-ratio wing. For variable-sweep wings a high-energy vortex flow is generated by the highly swept inboard fixed portion of the wing. As discussed in paper no. 5 by Ray, Lockwood, and Henderson, this vortex flow contributes to a loss of static longitudinal stability at high angles of attack. Therefore, the designer attempts to suppress the development of this vortex flow on variable-sweep wings by using appropriate flow-control devices. Typical effects achieved by such devices are presented in paper no. 5 and will not be considered further herein. For low-aspect-ratio wings the leading-edge vortex flow has the favorable effect of increasing the lift-curve slope, in addition to the unfavorable effect of reducing longitudinal stability at high angles of attack. Therefore, a quantitative understanding of the effects of vortex flow on low-aspect-ratio wings is required to achieve a trade-off between these favorable and unfavorable effects.

This paper presents the results of experimental and theoretical studies of vortex flow on low-aspect-ratio wings. The subjects to be discussed are summarized in figure 2. First, results of experimental studies to determine the longitudinal aerodynamic characteristics of a family of low-aspect-ratio double-delta wings are summarized. Second, flow visualization studies to determine the origin and development of the vortex flow pattern are presented and discussed. Finally, some of the existing theories for predicting the effects of vortex flow are briefly reviewed and a new theoretical approach, which eliminates some of the assumptions and constraints of past theoretical methods, is described.

MODEL AND APPARATUS

The model used in the experimental portion of this investigation is shown in figure 3. The basic wing had a trapezoidal planform with an aspect ratio of 1.69, a taper ratio of 0.12, and a leading-edge sweep angle of 59°. Various double-delta planforms were obtained by adding various sizes of strakes to this basic planform. These strakes had a leading-edge sweep angle of 77°. This model was tested in the Ames 40- by 80-foot wind tunnel at a Reynolds number of about 15 million.

REDUCTION OF DATA

The data from this investigation were reduced to coefficients based on the total wing area and mean aerodynamic chord of the equivalent delta wing. The equivalent delta wing was selected to have the same exposed wing area and span as that of the particular double-delta wing under construction. The reference dimensions of the equivalent delta planforms and those of the total theoretical planforms are listed in table I.

DISCUSSION OF RESULTS

Experimental Studies

The effects of changing the wing planform by adding various strakes to the basic wing are shown in figure 4 which presents lift coefficient as a function of angle of attack. These results show that, at low lift coefficients, the addition of the strakes reduced lift-curve slope, as would be expected since adding the strakes reduced the aspect ratio of the wing. However, adding the strakes also caused a significant increase in the lift-curve slope at high values of lift coefficient. At lift coefficients greater than 0.6 planforms with strakes require less angle of attack than the basic wing to obtain a given lift coefficient. Thus, at high angles of attack, the favorable effects of the strakes on the nonlinear portion of the lift (which is due to leading-edge vortex flow) more than offset the unfavorable effect on lift-curve slope due to the reduction in aspect ratio. It should be noted that the wing with the small strake produced slightly higher lift coefficients at high angles of attack than did the configuration with the large strake. Thus, it appears that there is an optimum strake configuration as far as improving lift-curve slope is concerned.

The effects of the strakes on the variation of pitching moment with lift coefficient are shown in figure 5. These results show that the intensified leading-edge vortex flow caused by the addition of the strakes reduced the static longitudinal stability at lift coefficients greater than 0.6. This illustrates a key problem in wing design, that is, how to obtain the favorable effects of the strakes on lift without suffering an unacceptable loss in longitudinal stability.

The effect of the strakes on the drag characteristics of the model are shown on figure 6. These results show that the strakes reduced the drag due to lift for lift coefficients above 0.6. This reduction, of course, results from the increased lift-curve slope due to the strakes discussed previously. Thus, the increased vortex flow promoted by the strakes reduced the drag due to lift at high lift coefficients by an amount which more than offset the increase in drag due to lift caused by the reduction in aspect ratio.

Since leading-edge vortex flow is associated with flow separation from the wing leading edge, it would be expected that the use of flow control devices on the wing leading edge should have a significant effect on the aerodynamic characteristics due to vortex flow. The effects of using a full span nose flap on the wing planform employing the small strake (aspect ratio equal to 1.49) are shown on figure 7. These results show that the nose flaps suppressed the formation of leading-edge vortex flow, and thus extended the linear portion of the lift curve to higher angles of attack and significantly reduced the magnitude of the nonlinear lift.

The effect of the nose flaps on pitching moment is shown in figure 8. These results show that the suppression of the vortex flow by the nose flaps alleviated the reduction in longitudinal stability at lift coefficients above 0.6.

The effect of the nose flaps on the variation of drag with lift is presented in figure 9, which shows that the use of the nose flaps produced a reduction in the drag due to lift. This reduction is contrary to what might be expected since, as previously discussed, the nose flaps reduced the lift-curve slope. However, the deflected nose flaps provided a forward-facing surface which allowed the realization of enough leading-edge suction to more than compensate for this reduction in lift-curve slope.

In order to gain some insight into the fundamental aspects of the flow producing these results, and also to serve as a guide in setting up theoretical models able to predict these results, various flow visualization studies were made. The results of one of these studies is shown in figure 10. This photograph shows the vortex flow over a small-scale double-delta wing body configuration installed in the Ames 7- by 10-foot wind tunnel. (This model was geometrically similar to the large-scale 1.49 aspect-ratio wing configuration tested in the 40- by 80-foot wind tunnel described previously.) The vortices shown in figure 9 were made visible by the natural condensation of the water vapor in the air in the wind tunnel as it flowed over the wing leading edge. One vortex originated at the juncture of the leading edge of the strake with the fuselage. The other vortex formed in the vicinity of the juncture of the strake leading edge with the basic wing leading edge. Vorticity, of course, is being shed from the full length of the wing leading edge. The portions of this flow which are visible in figure 10 are only those where the temperatures induced by this vorticity were low enough to condense the water vapor in the wind-tunnel air. It should be noted that there is a strong interaction between the two vortices over the aft portion of the wing, and that the resulting flow is nonconical.

From these flow visualization studies it appears that the following factors must be considered in any complete theoretical treatment of leading-edge vortex-flow phenomena. First, the theory must not be restricted to conical flows, since for many wing planforms of current interest, the flow is nonconical over large portions of the wing. Second, the interaction of the various vortices with each other must be allowed for. And, third, some means must be attained for establishing the strength of the vortex shed from the various portions of the wing leading edge.

Theoretical Studies

Some of the better-known methods for predicting vortex lift are summarized in figure 11. As shown in the upper left-hand corner of this figure, the flow is separated into two parts for theoretical treatment; a linear part which is predicted by conventional lifting surface theory; and a nonlinear part which is due to the leading-edge vortex flow (termed vortex lift). One of the oldest and easiest methods of predicting vortex lift is that of crossflow theory (ref. 5). The flow model used for this theory is shown in the upper right-hand corner of figure 11. To estimate the magnitude of the vortex lift this method treats the flow in the crossflow plane as that around a flat plate with an assumed drag coefficient. The advantage of this method is that it is simple and easy to use. The disadvantages are that it depends on the assumed crossflow drag coefficient, and that it is not adequate for handling the effects of vortex interaction. Another well-known theoretical method for predicting the effects of leading-edge vortex flow is that of Brown and Michael (ref. 3). The mathematical model used by Brown and Michael is shown in the lower left-hand corner of figure 11. This model is composed of the wing, two vortex lines above the wing leading edge, and two flat vortex sheets which connect the wing and the vortex lines. The strength and position of the vortex sheets and the vortex lines are determined by applying the Kutta condition to the flow at the wing leading edge, and requiring that the total force on the vortex system be zero. The advantage of the Brown and Michael approach over that of crossflow theory is that it does not depend on any empirical or arbitrary constants. However, it overpredicts the vortex lift by about a factor of 2. In addition, the vortex configuration is assumed at the start, so that subjects such as vortex interaction or the dependence of the vortex system on wing leading-edge geometry cannot be treated. Another theoretical method for predicting the effects of vortex lift is that due to Mangler and Smith. The mathematical model used by Mangler and Smith is shown in the lower right-hand corner of figure 11. This model is considerably more representative of the actual vortex flow over simple delta wings than that of Brown and Michael; consequently, the results are in better agreement with experiment so far as simple delta wings are concerned. However, the method of Mangler and Smith is restricted to conical flow, and, further, is mathematically complex and difficult to extend to nonconical flows.

Because of the inadequacies and restrictive nature of the various existing theories, Ames Research Center contracted the Vidya Division of Itek Corporation to develop a theory for predicting the lift and pitching moment due to vortex flow on low-aspect-ratio wings of arbitary planform. This theory is still being developed and therefore, the discussion to follow is more in the nature of a progress report than a presentation of a completed work. Some of the basic elements of the mathematical model used in this theory are shown in figure 12. The mathematical model is called the N-vortex flow model because the theory has been based on an arbitrary number of vortices being shed from the wing leading edge as indicated by the sketch on figure 12. As shown by this sketch, the basic idea of this theory is that the vortices will be shed at each of N chordwise stations along the wing leading edge. Once shed, these vortices will be allowed to interact or roll up with each other in any way that is required to maintain a completely force-free vortex system. Some of the basic assumptions of this theory are listed in figure 12. The vortex strength, initial position, and initial velocity are determined by an analysis in the crossflow plane as indicated by the sketch in the lower left-hand corner of figure 12. Thus, this portion of the analysis inherently assumes the restrictions of slender body theory. The vortex is shed so as to satisfy the Kutta condition at the wing leading edge. This, of course, includes consideration of the combined effect of all of the vortices present at that particular wing station. Some of the advantages of this theoretical approach are that (1) it distributes the vorticity along the wing leading edge in a quasi-sheet, (2) it allows the vortices to interact and roll up as they do in the real flow, and (3) it is not restricted to conical flow. Thus, this theory should prove useful for studying the effects of wing geometry changes on vortex-flow phenomena. Some of the disadvantages of this theoretical method are as follows: (1) the method is numerically complex (however, it has been programmed for solution by digital computers, so this is not a serious problem), (2) the Kutta condition is satisfied only at discrete points (i.e., only at the chordwise stations where the vortices are shed), and (3) the determination of the strength of the vorticity being shed along the wing leading edge is difficult. This latter shortcoming, however, is common to all of the theoretical methods, and is considered to be the key problem to be resolved in future work. In particular, for general application of the theory it is necessary to be able to establish the strength of the vorticity being shed along the wing leading edge as a function of wing leading-edge geometry, that is, angle of sweepback, leading-edge radius, leading-edge camber (such as provided by nose flaps), etc.

Figure 13 presents some preliminary results obtained from the N-vortex theory along with theoretical results obtained by the methods of Brown and Michael and Mangler and Smith. Also shown on figure 13 are experimental results obtained by Bartlett and Vidal. These results were obtained for a simple delta wing with sharp leading edges and with an aspect ratio of 1.50. The total normal-force curves shown for the various theoretical methods were obtained by adding the normal force predicted by the various theories for the leading-edge vortex flow to the normal force predicted by the linear lifting surface theory of Lawrence (ref. 6) for the unseparated flow. The N-vortex theory used in these calculations employed 48 vortex elements. This comparison shows that the results obtained from the N-vortex theory agree with those obtained by the method of Mangler and Smith, and that both of these methods show better agreement with experiment than does the method of Brown and Michael. However, both the N-vortex and the Mangler and Smith theoretical results overpredict the lift by about 20 percent.

The variation of pitching moment with angle of attack predicted by these same theoretical methods is shown in the lower right-hand corner of figure 13, along with the experimental results of Bartlett and Vidal. As was the case for the normal-force characteristics just discussed, the various theoretical methods overpredict the effects of vortex flow on pitching moment. However, much closer agreement of theory with experiment is obtained when pitching-moment coefficient is plotted as a function of normal-force coefficient. Thus it appears that the main discrepancy in the prediction of pitching moment is due to errors in predicting normal force as a function of angle of attack rather than to errors in the distribution of the normal force over the wing surface. This discrepancy is believed to be due to errors in estimating the strength of the vorticity shed from the wing leading edge in the theoretical methods. As noted previously, this is considered to be the key problem in all of the theoretical methods. Additional work is required to establish the strength of vorticity shed from the wing leading edge in order to improve and extend the theoretical methods. This work should include the effects of the fuselage, wing leading-edge sweep, and wing leading-edge radius on vortex strength, since it is known that these effects are large. Further, many aircraft designs of current interest (e.g., hydrogen-fueled hypersonic aircraft) will have large fuselages relative to the wing, and blunt wing leading edges.

CONCLUDING REMARKS

In summary, these studies have shown that vortex flow effects are important on a variety of modern wing configurations. It should be noted that, while this discussion has treated only longitudinal characteristics, it is well-known that vortex-flow phenomena have powerful effects on lateral directional characteristics, and further, that these effects are generally more difficult to predict than the longitudinal effects. While existing theories predict the correct trends, they are overly restrictive in their assumptions as to the mathematical model assumed to represent the vortex flow and generally are not accurate enough for design purposes. The new N-vortex theory appears promising, but additional work is required to establish the strength of the vorticity shed from the wing leading edge as a function of airplane geometry.

REFERENCES

1. Bollay, William: A Non-Linear Wing Theory and Its Application to Rectangular Wings of Small Aspect Ratio. Z. Angew. Math. Mech. Bd. 19, Nr. 1, Feb. 1939, pp. 21-35.

2. Mangler, K. W.; and Smith, J. H. B.: Calculation of the Flow Past Slender Delta Wings With Leading Edge Separation. Rept. No. Aero.2593, British R.A.E., May 1957.

3. Brown, Clinton E.; and Michael, William H., Jr.: On Slender Delta Wings With Leading-Edge Separation. NACA TN 3430, 1955.

4. Bartlett, G. E.; and Vidal, R. J.: Experimental Investigation of Influence of Edge Shape on the Aerodynamic Characteristics of Low Aspect Ratio Wings at Low Speeds. J. Aeron. Sci, vol. 22, no. 8, Aug. 1955, pp. 517-533, 588.

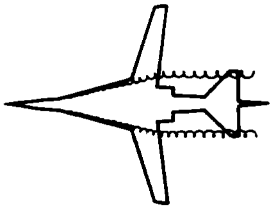
5. Betz, A.: Applied Airfoil Theory. Vol. IV of Aerodynamic Theory, div. J, ch. III, sec. 7, W. F. Durand, ed., Julius Springer (Berlin), 1935 (reprinted by Durand Reprinting Committee, 1943), pp. 69-72.

6. Lawrence, H. R.: The Lift Distribution on Low Aspect Ratio Wings at Subsonic speeds. J. Aeron. Sci., vol. 18, no. 10, Octo. 1951, pp. 683-695.

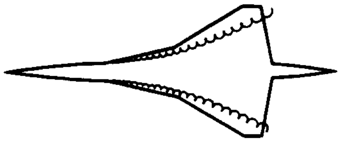
TABLE I.- WING PLANFORM REFERENCE DIMENSIONS

Basic wing	
Theoretical planform	
Total wing area, ft^2	439
Exposed wing area, ft^2	333
Span, ft	27.3
Mean aerodynamic chord, ft	19.4
Aspect ratio	1.69
Taper ratio	0.123
Equivalent delta planform	
Total wing area, ft^2	461
Exposed wing area, ft^2	333
Span, ft	27.3
Mean aerodynamic chord, ft	22.5
Aspect ratio	1.62
Taper ratio	0
Basic wing plus small strake	
Theoretical planform	
Total wing area, ft^2	512
Exposed wing area, ft^2	358
Span, ft	27.3
Mean aerodynamic chord, ft	25.4
Aspect ratio	1.46
Taper ratio	0.082
Equivalent delta planform	
Total wing area, ft^2	501
Exposed wing area, ft^2	358
Span, ft	27.3
Mean aerodynamic chord, ft	24.5
Aspect ratio	1.49
Taper ratio	0
Basic wing plus large strake	
Theoretical planform	
Total wing area, ft^2	555
Exposed wing area, ft^2	387
Span, ft	27.3
Mean aerodynamic chord, ft	28.3
Aspect ratio	1.34
Taper ratio	0.075
Equivalent delta	
Total wing area	542
Exposed wing area	387
Span, ft	27.3
Mean aerodynamic chord, ft	26.4
Aspect ratio	1.38
Taper ratio	0

EFFECT OF LEADING-EDGE VORTEX FLOW



- VARIABLE–SWEEP WINGS
  1. REDUCES LONGITUDINAL STABILITY



- LOW-ASPECT-RATIO WINGS
  1. INCREASES LIFT-CURVE SLOPE
  2. REDUCES LONGITUDINAL STABILITY

Figure 1

SUBJECTS TO BE DISCUSSED

- EFFECTS OF VORTEX FLOW ON AERODYNAMIC CHARACTERISTICS

- FLOW VISUALIZATION STUDIES

- THEORETICAL TREATMENT OF VORTEX FLOW

Figure 2

LOW-ASPECT-RATIO WING MODEL

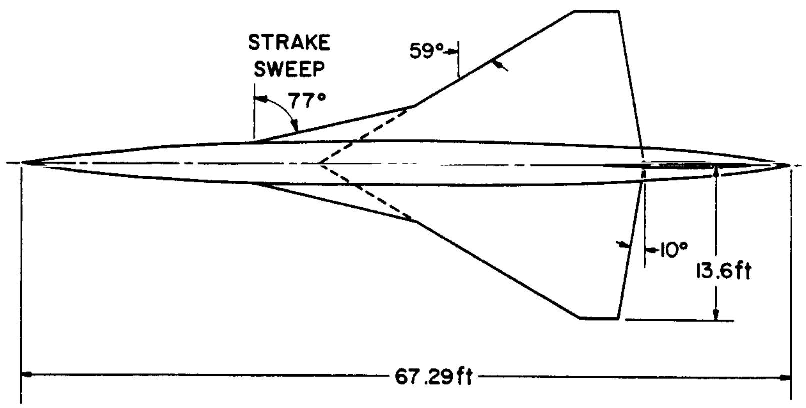


Figure 3

EFFECT OF PLANFORM ON LIFT

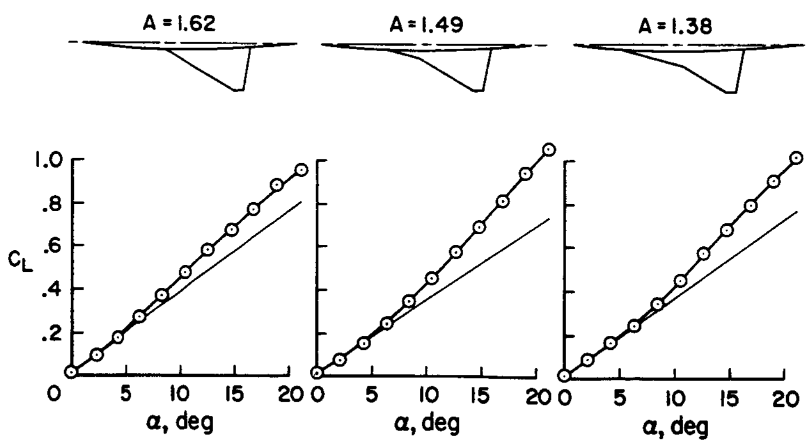


Figure 4

EFFECT OF PLANFORM ON PITCHING MOMENT

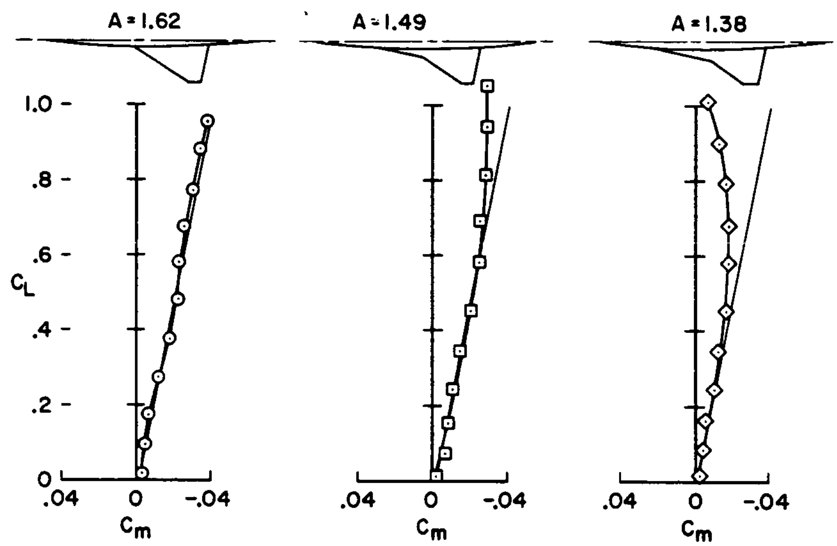


Figure 5

EFFECT OF PLANFORM ON DRAG

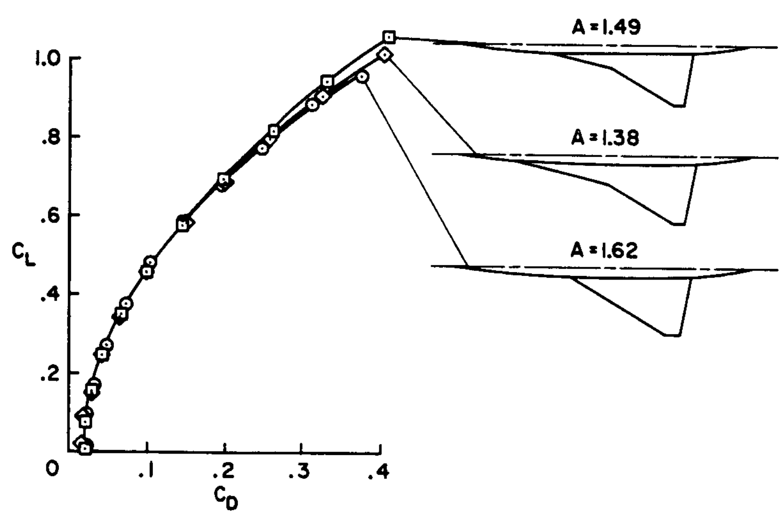


Figure 6

EFFECT OF NOSE FLAPS ON LIFT

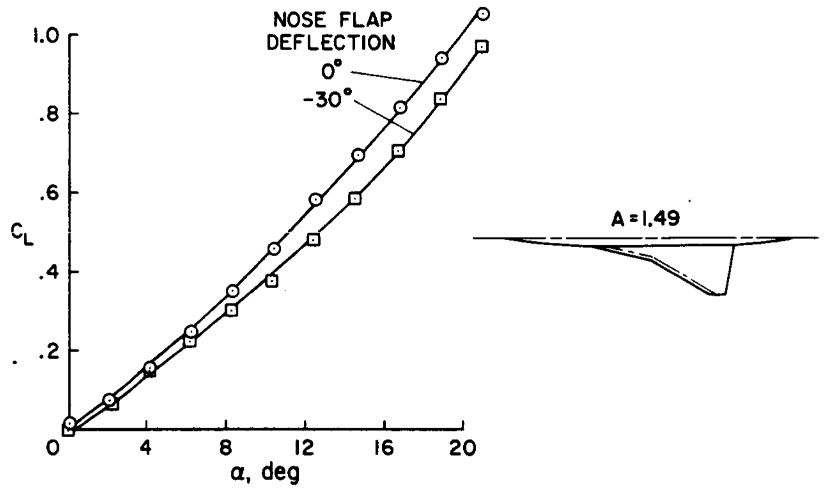


Figure 7

EFFECT OF NOSE FLAPS ON PITCHING MOMENT

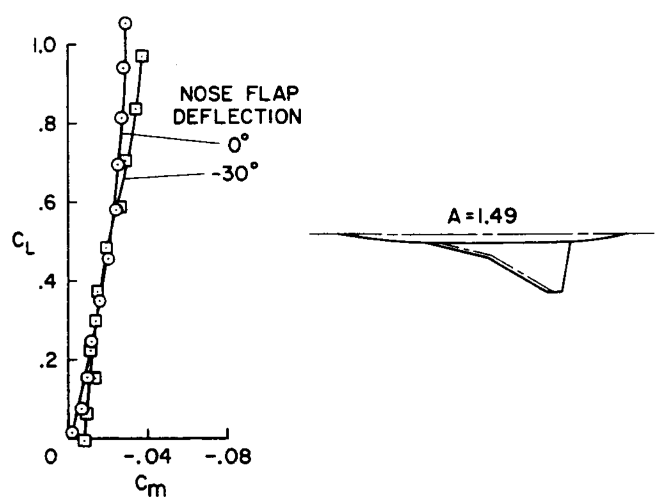


Figure 8

EFFECT OF NOSE FLAPS ON DRAG

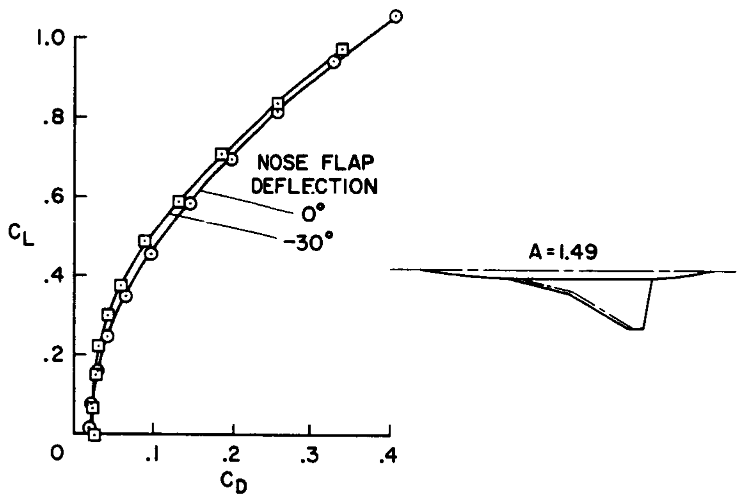


Figure 9

VORTEX FLOW ON DOUBLE-DELTA WING

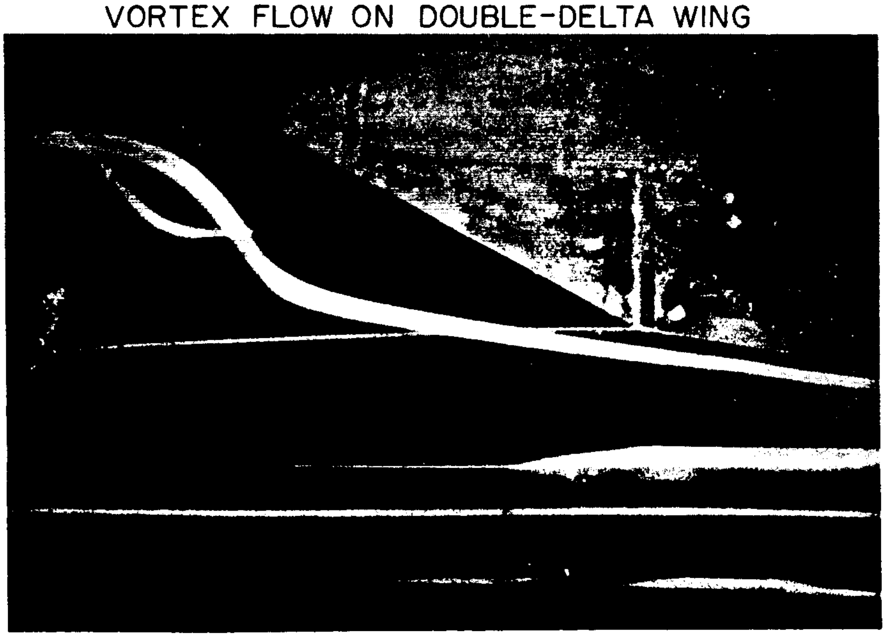


Figure 10

AAA112-9

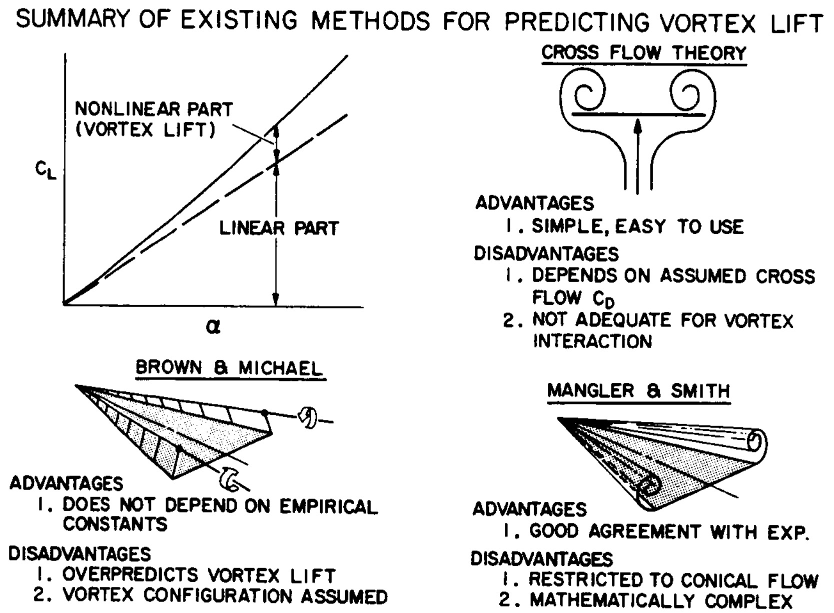


Figure 11

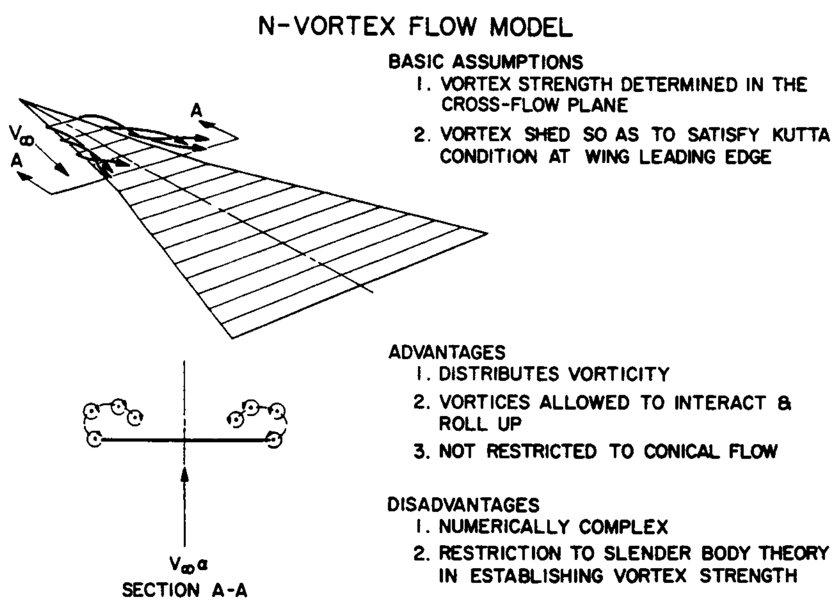


Figure 12

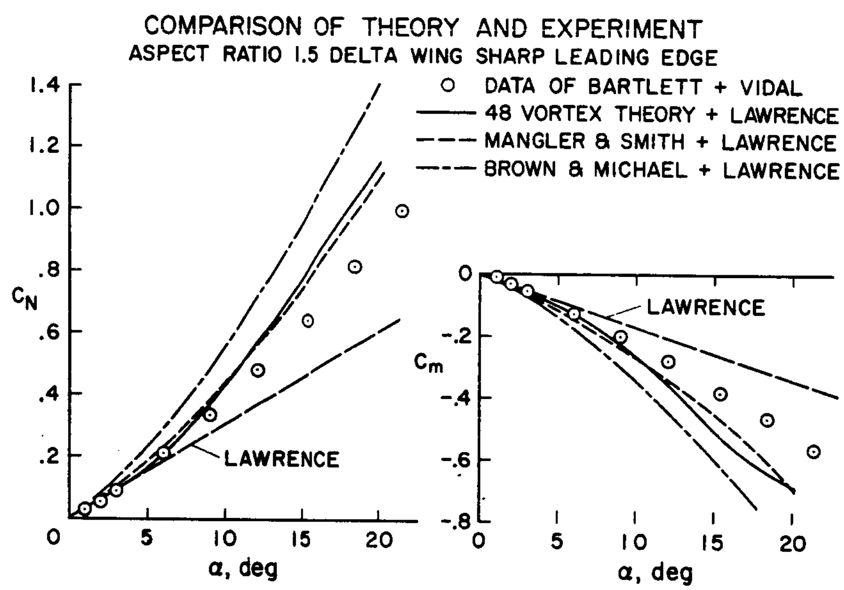

COMPARISON OF THEORY AND EXPERIMENT
ASPECT RATIO 1.5 DELTA WING SHARP LEADING EDGE
DATA OF BARTLETT + VIDAL
48 VORTEX THEORY + LAWRENCE
MANGLER & SMITH + LAWRENCE
BROWN & MICHAEL + LAWRENCE
C_N
1.4
1.2
1.0
.8
.6
.4
.2
0
LAWRENCE
5
10
15
20
α, deg
C_m
0
-.2
-.4
-.6
-.8
LAWRENCE
0
5
10
15
20
α, deg

Figure 13