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LEADING-EDGE VORTEX RESEARCH: SOME NONPLANAR CONCEPTS AND CURRENT CHALLENGES

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SUMMARY

This paper provides some background information for the Vortex Flow Aerodynamics Conference and shows that current slender wing airplanes do not use variable leading-edge geometry to improve transonic drag polar. Highlights of some of the initial studies combining wing camber, or flaps, with vortex flow are presented. Current vortex flap studies were reviewed to show that there is a large subsonic data base and that transonic and supersonic generic studies have begun. There is a need for validated flow field solvers to calculate vortex/shock interactions at transonic and supersonic speeds. Many important research opportunities exist for fundamental vortex flow investigations and for designing advanced fighter concepts.

INTRODUCTION

In recent years, NASA and the AFWAL have become more concerned about the impact of separation-induced vortex flows on the design and off-design performance of military aircraft (refs. 1 and 2). The Advanced Tactical Fighter, as discussed recently by Piccirillo (ref. 3), is being considered to provide a significant increase in supersonic cruise efficiency over current fighters, while maintaining an equivalent transonic maneuver capability. This type of design is very challenging since optimum supersonic designs tend toward slender highly swept wings with low aspect ratio, while transonic designs have higher aspect ratios to help improve cruise and maneuver performance.

Much research has been conducted to try to bridge the gap between transonic and supersonic mission requirements by utilizing variable camber concepts such as leading-edge flaps and slats. Designed with attached flow, these leading-edge devices have been successfully employed on a variety of airplanes with low-to-moderate leading-edge sweep angles. However, application to slender, higher swept wings is limited by the onset of separated flows. An alternate design approach is to let the flow separate from the leading edge and use the vortex-induced suction pressures acting on a drooped leading edge to recover some of the leading-edge suction lost due to leading-edge separation. The current Vortex Flow Aerodynamics Conference brings together specialists to address wing leading-edge vortex flows and vortex flaps in particular.

The present paper is one of two background papers for the conference, and complements the information presented by Polhamus (ref. 4). The present paper reviews some of the current military aircraft which use variable leading-edge geometry to improve drag polar, and highlights some of the initial studies combining wing camber, or flaps, with vortex flow. The status of current vortex flap research will be presented, along with appropriate vortex theories which will be discussed during the conference. Some technical challenges will be discussed to highlight additional vortex flow research areas of interest. An extensive reference list is also included.

SYMBOLS

A	aspect ratio of the wing
C_D	drag coefficient
C_L	lift coefficient
C_p	local pressure coefficient
$\bar{c}$	reference chord
c_r	root chord
FVS	Free Vortex Sheet
LE	leading edge
L/D	lift-to-drag ratio
M	Mach number
M_N	Mach number normal to the leading edge
p	nondimensional camber height for conically cambered wings in terms of local semispan
R	Reynolds number
$R_{\bar{c}}$	Reynolds number based on mean aerodynamic chord
s	local semispan
S	reference area
VLM	Vortex Lattice Method
VLM-SA	Vortex Lattice Method coupled with the suction analogy
x/c	fractional distance along a local chord
$2y/b$	fractional distance along the semispan

$y/s_{\delta_n = 0}$ local lateral distance, nondimensionalized by semispan with flap undeflected

$z/s_{\delta_n = 0}$ local vertical distance, nondimensionalized by semispan with flap undeflected

α angle of attack

α_N angle of attack normal to wing leading edge

δ_n leading-edge flap deflection angle, positive down, measured normal to the hingeline

δ_{TE} trailing-edge flap deflection angle, positive down, measured normal to the freestream

ΔC_D drag due to lift in figures 3 and 6, vortex flap increment in figure 18

Λ_{LE} leading-edge sweep angle defined in figure 1

AIRCRAFT GEOMETRY AND DRAG DUE TO LIFT

Aircraft Geometry

In order to understand the importance of sweep and variable camber in the design of advanced aircraft, it is of interest to examine current airplane configurations for geometric trends.

There are many ways to represent airplane geometric variables. We have shown aspect ratio as a function of leading-edge sweep angle in figure 1, where Λ_{LE} is defined in the sketch. In order to be able to plot an airplane whose wing has more than one sweep angle, such as a double-delta or ogee planform, an effective sweep angle is defined by a line drawn from the apex of the reference planform to the leading edge of the tip chord. The data for the configurations were extracted from information in references 5 to 8, and are listed in Table I along with the symbol definition.

The data fall into two groups, one for fixed sweep and one for variable sweep, and show the obvious decrease in aspect-ratio with increase in sweep angle. The question which concerns us is which airplanes have variable leading-edge geometry and use that capability to improve drag polar. The solid symbols represent those aircraft. All variable leading-edge geometry is incorporated on wings with sweep angle less than 50°, with the exception of the Mirage 2000 and 4000 aircraft which have a sweep angle of 60°. A photograph of the Mirage 2000 with its variable leading-edge flaps deployed is presented in figure 2 (taken from ref. 9).

All of these variable flap configurations were designed to utilize attached flow for subsonic or transonic maneuver requirements. It is not known for what flow field the Mirage 2000 and 4000 flaps are designed. One of the problems with increasing the wing sweep angle is that it gets more difficult to keep the flow from separating. Simple sweep theory suggests that the C_L where the wing first experiences flow separation is lower for the higher swept wing. This is due to the higher upwash at the leading-edge and larger section lift coefficients. Drooping the leading edge to keep the flow attached is effective at low lifts, but this shifts the pressure peak to the flap hingeline and ultimately results in hingeline separation.

For most of the fighter airplanes which have no variable leading-edge devices, wind tunnel studies of leading-edge flaps were conducted during the developmental stages of their projects. These data were then used to decide whether the aerodynamic benefits outweighed the penalties for incorporating them in the system. The benefits have not been large enough to pay for themselves, and the data are subsequently filed away, unpublished, because they were not "successful" and because the program is a proprietary one. This has been the case for the Viggen and F-16XL airplanes. The reason why variable flap-systems did not work is because separated flows dominate these slender wing configurations. In particular, the reattachment line for the laeding-edge separation-induced vortex progresses quickly over the flap and onto the wing upper surface. Once this occurs, the vortex-induced suction pressures increase lift, but the flap becomes less effective for reducing drag. This has been a very difficult flow field for which to design drag-efficient shapes.

Subsonic Drag Due To Lift

The problem of achieving efficient drag polars is addressed in figure 3, which presents subsonic drag-due-to-lift data as a function of aspect ratio for a number of airplane models. The untrimmed data are plotted at a constant C_L of 0.5 and were obtained from references 10 to 20 for M = .6 to .8. The solid symbols represent composite drag polars obtained from leading-and trailing-edge flap deflections. As would be expected, the results show that the aircraft with the higher aspect ratios have lower C_D, and, since flow control devices are used, these drag levels approach the full suction values. Decreasing aspect ratio results in higher drag for several reasons. There is a potential flow increase due to lower aspect ratio, the higher swept slender wings are less efficient in achieving high suction levels than the non-slender wing, and the low-aspect ratio wings do not use variable leading-edge flaps to achieve an optimum polar. The higher swept configurations have a fixed camber. Note that there were no data available for the Mirage 2000 or 4000.

Drag values are presented for a series of planar delta wings to give a reference condition. The data (ref. 13) correlate with the vortex lift estimates with zero suction (ref. 16). The F-16XL drag value departed from the data trend established by the Viggen, Mig-21, and F-106 aircraft. One reason for the higher maneuver drag for these slender wings is that they have a fixed camber shape that must function over a wide range of subsonic to supersonic cruise and transonic maneuver requirements. The high sweep angle at maneuver lifts results in a leading-edge vortex flow, and, hence, vortex lift. The loss of leading-edge suction leads to higher drag. These data suggest that there is a new design space available where variable leading-edge devices have seldom been used. As noted by Polhamus (ref. 4), there are many advantages of vortex flows which are designed into current fighters, such as the F-16, F-18, and the F-16XL. Note too that LE suction is not the only measure of fighter capability. Other factors, such as wing loading, instantaneous turn capability, agility, range, weapons carriage, etc., are some of the important measures. Also recall that the data are for a constant C_L and are untrimmed. Data trimmed at a constant load factor would provide a more definitive analysis.

The question is how do you make variable camber devices effective on higher swept configurations. There are two basic approaches to this problem. The classical approach is to keep the flow attached at the leading edge by drooping the leading edge into the upwash to lessen the leading-edge pressure peak. The reader is referred to references 21 and 22 for some early studies on delta wings. In the limit, the drooped leading edge matches the upwash which gives attached flow. The flow gradients are so strong at the hingeline, however, that the flow separates and forms a vortex aft of the hingeline and over the wing; this vortex gives a little increase in lift and a very large increase in drag. An alternate approach to this is to encourage the leading-edge flow to separate and use the resulting vortex flow to induce suction pressures on the forward-facing surface. Here also, the wing leading-edge is drooped into the upwash field, but you want the stagnation line to remain on the lower surface to insure upwash, and, hence, a vortex, all down the leading edge. For the remainder of the paper, we will be discussing some of the vortex flow research that began by looking at combining camber with the vortex flow, discuss how it evolved to the vortex flap concept, review the status of current vortex flap studies, discuss progress in vortex flow theories, and mention some challenges for additional vortex research.

COMBINING WING CAMBER OR FLAPS WITH VORTEX FLOW

The purpose of this section is to provide a historical perspective of research that has been conducted to evaluate the effects of combining wing camber or flaps with leading-edge vortex flow. In particular, we will highlight some of the research that has been conducted during the past 10 years which helped give rise to the current NASA/AFWAL Vortex Flow Aerodynamics Conference. Combining the effects of wing camber or leading-edge flaps with the leading-edge vortex is a relatively new research area. The reader is referred to references 23 to 27 for some excellent state-of-the-art review papers which have been published over the past 8 years and contain a considerable number of references.

Some Initial Studies

Wentz's Experiment.- In 1972, Wentz (ref. 28) investigated the effects of leading-edge camber on the low-speed aerodynamics of slender delta wings. Apex and conical cambers were tested along with constant chord leading-edge flaps, which approximated the apex camber leading edge. An example of pressure data is shown in figure 4 for the conical camber configuration at $\alpha = 10.3°$. The vortex reattachment line, indicated by the arrow, was obtained from tuft data. Recent analysis of the drag polar data for this conical camber configuration showed a suction level of about 40 percent at a C_L of 0.31 ($\alpha = 10.3°$), and about 28 percent at a $C_L = 0.5$.

Vortex Theories for Nonplanar Wings.- During the 1970's three theories were developed to calculate the vortex flow aerodynamics of cambered slender wings: conical flow, the Vortex Lattice Method-Suction Analogy, and the Free Vortex Sheet. These are shown in figure 5, taken from a 1978 paper by Lamar (ref. 29), and represent different levels of capability. The conical flow technique of Barsby (ref. 30) modeled the separated flow vortex sheet, but does not satisfy the trailing-edge Kutta condition. The Vortex Lattice Method - Suction Analogy (VLM-SA) was a modified version of the original suction analogy where Lamar accounted for a vortex lift vector for cambered and twisted wings. The Free Vortex Sheet (FVS) method, originally developed by the Boeing Company in 1974, does account for the trailing-edge Kutta condition (ref. 31), and gives completely three-dimensional flow field calculations.

An important factor in the evolution of these theories from initial development was the critical correlation and validation studies. One example is the study by Kuhlman (ref. 32) who correlated pressure distributions obtained with the FVS code with Wentz's experiments for a conically cambered delta (ref. 28). Another example is Manro's investigation (ref. 33) to correlate FVS pressure distributions with experiment on an arrow wing having twist and camber.

The capability of these theories to estimate the effects of camber height on drag factor is shown in figure 6, taken from Lamar and Luckring (ref. 23). All of the theories predict a reduction in drag with an increase in camber height. However, because of its restricted assumptions, the conical flow method estimates lower drag than the FVS or VLM-SA techniques. For the range of camber heights shown here, the FVS and VLM-SA estimates are essentially the same. With this earlier version of the FVS, it was difficult to obtain converged solutions where the vortex was small and confined to a camber surface. Kuhlman (ref. 32) explored this difficulty for combinations of angle of attack and leading-edge droop, while Tinoco (ref. 34) performed one of the first studies using the FVS to design slender wing camber shapes to reduce drag.

Pre-Scamp Maneuver Design.- The first vortex design with the VLM-SA was produced by Lamar et al. (ref. 35) on the Pre-Scamp configuration shown in figure 7. This was part of a cooperative effort with General Dynamics to evaluate various transonic and supersonic (ref. 36) wing designs on a stretched F-16 fuselage. The tests were conducted in the NASA Langley Research Center 7- by 10-Foot High-Speed Tunnel (7x10 HST), in April 1978. The wing, which was designed for a maneuver C_L of 0.5, achieved the design flow field with the reattachment line occurring at the camber crest down the length of the wing and with attached flow downstream over most of the remainder of the wing. This resulted in a suction of 77 percent at the design point.

In addition to the fixed camber design, a planar wing was tested with leading- and trailing-edge flaps. The results are illustrated in figure 8, taken from reference 37, which shows L/D with Mach number for a cruise and maneuver condition. These data suggest that a combination of simple leading-edge and trailing-edge flaps could approximate the drag benefit due to the vortex flow at transonic maneuver, and that the same flaps at supersonic speeds (only the leading edge was deflected in these data, and at lower deflection angles) approach the L/D levels obtained for a fixed cruise camber. Polhamus described the NASA/GD co-op program in reference 27, where he presented another version of these data.

F-16 data (ref. 14) are shown to illustrate the effect of sweep, aspect ratio, and deflected flaps in going from a moderately swept transonic fighter to a slender supersonic-cruise-type fighter. The F-16 uses a combination of deflected flaps to optimize drag polar throughout its flight envelope. As noted in figure 8, the combination of increased sweep, or lower aspect ratio, and fixed camber for the slender wing reduces subsonic cruise and maneuver L/D and increases supersonic cruise efficiency. Using leading- and trailing-edge flaps on the slender wing lessens these subsonic reductions.

The Vortex Flap Concept

Early Wind Tunnel Studies Explore Flap Hypothesis.- After the Pre-Scamp data were available in April 1978, Rao began a series of experiments in the Langley 7x10 HST to explore the vortex flap concept. Simple generic models, such as a 74° delta (ref. 38) and a highly swept arrow wing (ref. 39), were used to build the data base and evaluate parametric sensitivities. The sketches in figure 9 were taken from reference 40 and illustrate the vortex on the basic wing with no control and the flow due to the vortex flap, where the vortex is on the flap with reattachment of the flow at the hingeline and attached flow over the remainder of the wing. Two types of flaps were suggested, one that has a simple inboard hinge, and the other a folding type that deploys out from the lower surface. An alternate approach for controlling the leading-edge vortex for highly swept wings was proposed by Runyan (ref. 41), who investigated the effect of a leading-edge tab counterdeflected from the main portion of the flap.

The vortex flap flow field was verified experimentally by Rao (ref. 39) using smoke flow, as observed in figure 10, for a segmented flap arrangement on an arrow wing. Pressure measurements by Schoonover and Ohlson (ref. 42) demonstrated the shift in the suction pressures onto the flap compared to the pressures on the basic supersonic camber configuration (fig. 11). Deflecting the flaps reduces lift at a given angle of attack; therefore, a flapped configuration must increase angle of attack to get back to the same lift. This is apparent in the sketch at $C_L = 0.5$, where $\alpha = 10.6°$ for the basic configuration, and $\alpha = 12.9°$ with the flap. Vortex-induced pressures on the flap resulted in significant reductions in drag.

A considerable amount of data has been obtained for vortex flaps applied to many different research models. The majority of studies have been performed in low-speed and subsonic wind tunnels and have investigated a variety of flap arrangements. For example, research has been conducted on leading-edge devices (refs. 43, 44, and 45), the tabbed vortex flap (refs. 46 and 47), the upper surface flap (ref. 48), segmented flaps (ref. 49), apex flaps (ref. 50), trailing-edge flap effects (ref. 51), planform studies (refs. 52, 53, and 54), and lateral-directional research (refs. 55 and 56).

Vortex Analysis and Design.- There has been a steady evolution in the capabilities of vortex theories to model more complicated flow and geometry situations. This is true of the suction analogy as well as the FVS code. Both Carlson (ref. 57) and Lan (ref. 58) have extended the capabilities of the suction analogy. Lan, for example, derived an improved formulation for the rotated suction vector location for subsonic and supersonic flow. Instead of assuming the vector to be normal to the camber slope at the leading edge, it is moved to a rearward location, where it acts perpendicular to the camber line to account for the size and growth of the vortex. This analysis method, along with that of Carlson, led to the development of design techniques by Chang and Lan (ref. 59) and by Carlson (ref. 60).

The FVS code continued to be developed and refined by Langley, Boeing, and Northrop researchers to predict the vortex flow aerodynamics for a variety of flow conditions and configuration geometries. The reader is referred to references 24 and 61 for several status reports on verification and application efforts with the code. In 1982, Luckring (ref. 62) demonstrated that convergence could be improved by using a coverged solution at a higher angle of attack as the starting solution for the next lower angle of attack. Additionally, vortex flap solutions were obtained by using a vortex sheet transfer technique, where the converged sheet geometry from one flap deflection was used as the starting geometry for the next flap deflection. This improved formulation was used by Frink (ref. 63) to obtain estimates of vortex-flow flap hinge moments, and by Erickson (ref. 64) to obtain solutions for vortex-flapped wings having reduced sweep angle. An example of Erickson's results is presented in figure 12 for a 65° delta wing with a conical flap. The results are for M = 0.6 and α = 15°. The converged sheet geometry is for a flap deflection of 30°, while the upper surface pressure distributions and vortex core positions are for flap deflections from 0° to 40°. Manro (ref. 65) conducted a related study which was to utilize the FVS code to predict the aeroelastic loads for an arrow wing.

A critical feature of the vortex flap flow field is the location of the reattachment line with respect to the flap hingeline. Frink (ref. 66) has developed a design procedure which achieves this type of flow, as is sketched in figure 13. The design technique came about as an attempt to add rationale to shape the flap to accommodate the vortex growth.

STATUS FOR VORTEX FLOW AERODYNAMICS CONFERENCE

The current Vortex Flow Aerodynamics Conference provides state-of-the-art papers on advances in vortex flow theories, as well as on vortex flap research over the past few years. This section of the paper gives a brief review of progress in vortex flap research, provides some needs for additional work, and presents highlights of research activities under way in vortex theories.

Vortex Flap Studies

Subsonic.- A large subsonic data base has been established for the vortex flap concept. As noted in figure 14, this includes pressure and load distributions, hinge moments, performance, longitudinal and lateral stability and control, and flow field diagnostics. Flap geometric variations include flap planform, hinge-line sweep, flap deflections, and flap and wing aerodynamic sections. The types of flaps, shown in figure 15, have increased to include upper surface, lower surface, and apex types. Most of the results presented at the conference are for the lower surface folding or hinged types of flaps. Hoffler presents results of studies on apex fences (ref. 67), while Rao discusses a new type of lower surface flap called a cavity vortex flap (ref. 68).

As suggested in figure 16, the flap concept is maturing at subsonic speeds because of the number of application studies which combine experiment with theoretical analysis and design methods. The sketches in figure 17 are an updated version of Schoonover's (ref. 69) and illustrate the variety of configurations for which flaps have been applied. Papers are presented at the conference on subsonic studies of both generic (refs. 70 to 74) and aircraft (refs. 17 and 18, and 75 to 77) types of models.

An example of data for aircraft models (from ref. 69) is shown in figure 18 to illustrate the effect of vortex flaps on subsonic drag reduction for the F-106, F-16XL, and the AFTI/F-111 configurations. Design studies for these three configurations are published at the conference and extend Frink's vortex-flap design procedure for simple delta wings (ref. 78), to wings with twist and camber, such as the F-106 delta wing (ref. 17), the F-16XL cranked wing (ref. 18), and the AFTI/

F-111 swept-wing panel (ref. 77). The parameter ΔC_D is defined as the difference between the baseline drag with no flap and the configuration drag after the flap is added. The drag reduction increases with increased lift to about 200 to 250 drag counts near the design point. NASA Langley is considering a subsonic flight experiment on an F-106 airplane to verify the vortex-flap flow field and design procedure. An initial study of the vortex flow field over the F-106 is described by Lamar in reference 79.

Transonic/Supersonic.- Considerably fewer studies have been conducted at transonic and supersonic speeds than at subsonic speeds (see fig. 19). Some transonic data are provided by Klein (ref. 80) on a generic fighter model which had three highly swept wing planforms, for which a number of vortex flaps were designed. Hallissy (ref. 17) and Finley (ref. 18) present transonic results obtained on aircraft models of the F-106 and F-16XL, respectively.

Research at supersonic speeds has begun using generic models to study leading-edge vortex flows and their impact on supersonic aerodynamic performance. For example, Miller and Wood (ref. 81) investigated the leeside flow fields over planar delta wings, and classified the test data by the flow conditions normal to the wing leading edge. This is presented in figure 20. Recent supersonic studies (refs. 82 and 83) have examined delta wing aerodynamics in terms of upper and lower surface contributions and have assessed available prediction methods for estimating leading-edge vortex aerodynamics for planar and cambered delta wings. These evaluations suggest that additional codes are needed to analyze the vortex/shock interaction and the flap hingeline separation phenomena. These supersonic efforts are summarized by Miller in reference 84.

Leading-Edge Vortex Theories

Suction Analogy for Analysis and Design.- Considerable use has been made of the leading-edge suction analogy for providing preliminary analysis and design. In 1983, Lamar and Campbell (ref. 26) reviewed the extensions to the suction analogy that had been made to estimate strake-wing configurations, cambered wings, round leading edges, and a vortex breakdown criteria for estimating longitudinal and lateral-directional aerodynamics. Current extensions of the suction analogy principles are presented by Lan (ref. 85) which include the vortex action point, rounded leading edges, body vortex lift, and nonlinear wave drag for supersonic speeds (see fig. 21). In addition, the suction analogy has been incorporated into a number of design procedures. Frink (ref. 78) discusses the use of the analogy to design area efficient vortex flaps, while Lan (ref. 86) describes an optimization technique to design vortex flaps on wings for maximum L/D. Carlson (ref. 87) uses attainable thrust considerations to analyze and design wing flap systems. Huebner (ref. 88) describes an alternate procedure to Lan's (ref. 86) where a new optimizer is coupled with Lan's analysis to define vortex flaps at supersonic speeds.

Free Vortex Sheet Method.- The free-vortex-sheet method continues to provide the bulk of the subsonic flow-field calculations and integrated force and moment results to correlate with the various suction analogy and Euler codes. As noted in figure 21, Luckring (ref. 89) presents an updated version of the FVS formulation which has greatly improved convergence properties for a broad range of geometries, including vortex flaps. One of the recent innovations for the FVS was Luckring's work to develop a viscous core formulation to estimate vortex breakdown (ref. 90). Frink (ref. 72) obtains calculations for vortex flap pressure distributions and hinge moments for a 74° delta wing and shows the necessity for accounting for the secondary vortex in theoretical models. Additional application results are presented by Grantz (ref. 73) and Erickson (ref. 91).

Euler Codes.- Euler codes began appearing in the literature in 1982 and have been developing rapidly. The results shown in figure 21 were obtained by Raj (ref. 92) for a 71° swept arrow wing at M = 0.85 and α = 15.8°. The crossflow velocity field is shown for one location. The advantage of the Euler code is that it has the capability to compute very complicated flows such as the vortex/shock interactions. It is desirable to perform further subsonic validation studies between the Euler code vortex flows and wing surface pressures and the FVS code in order to take advantage of the large number of FVS solutions available. Recently, Kandil (ref. 93) used an integral equation approach to calculate a vortex/shock interaction on a delta wing.

Sirbaugh (ref. 94) presents a correlation study of Euler analysis for an elliptic missile body, while Raj (ref. 95) presents results of correlations with two cropped delta wings and an arrow wing. Newsome (ref. 96) provides a critical comparison between Euler and Navier-Stokes equations for the simulation of leading-edge vortex flows at supersonic speeds.

Three-Dimensional Boundary Layer Methods.- Three-dimensional boundary layer research is very important in order to get some viscous "smarts" into inviscid methods, such as the Free Vortex Sheet and Euler codes. Currently, separation lines must be specified for these codes. Recently, Wai (ref. 97) and DeJarnette (ref. 98) developed three-dimensional boundary layer techniques to estimate the boundary layer and secondary separation line on slender wings with vortex flows. The sketch in figure 22 is from reference 98. Woodson (ref. 99) and Blom (ref. 100) report on their respective techniques. Boundary layer techniques should be developed to estimate separation lines on slender wings with round leading edges, at leading-edge flap and trailing-edge flap hinge lines, and the secondary vortex separation line. This is a more critical problem at subsonic and transonic speeds where the Navier-Stokes solvers are not appropriate yet.

Navier-Stokes Solvers.- Navier-Stokes solutions are usually obtained for supersonic conditions so the solution domain is limited compared to the subsonic. An example of the flow detail is shown in figure 22 for a 75° delta wing at M = 1.95 and α = 10°. These results were obtained by Rizzetta (ref. 101) and demonstrate the upper surface flow pattern, including the primary vortex reattachment line and the secondary separation line. Supersonic studies reported at the conference include Newsome (ref. 96), Buter (ref. 102), and Blom (ref. 100). Studies need to be extended down to subsonic and transonic speeds. One approach would be to use a converged FVS solution for M = 0.9 as the starting solution to focus the grid and reduce run time.

SOME CHALLENGES FOR ADDITIONAL VORTEX RESEARCH

There are a number of opportunities to study flow field problems for slender wing configurations. These are listed here to provide some food for thought. Some of the research challenges are illustrated by flow situations on some current airplanes.

1. Combine attached flow and vortex flow fields in wing design.

2. Investigate vortex flow and shock wave interactions. An example is shown in figure 23 taken from reference 103 of an F-4 airplane at M = 0.95 and an angle of attack of 8°. Where the vortex has started on the outboard panel, there is no evidence of the shock in the surface oil flow. Inboard the attached flow proceeds to the trailing-edge shock. The separated vortex results in an oblique flow which lowers the local normal Mach number to subsonic. Theoretical models are needed to exploit this favorable flow interaction.

3. Continue to develop 3-D boundary layer techniques to estimate separation lines at round leading edges, leading-edge flap and trailing-edge flap hingelines, and secondary vortex flows.

4. Conduct critical studies of M and Rn scaling of vortex development. An example of this is shown in figure 24 for the F-111 TACT airplane at M = 0.6 and $\alpha = 6°$. These flight data were obtained by Schoonover (ref. 104) and illustrate a vortex-induced pressure distribution at $R_{\bar{c}} = 20 \times 10^6$; increase in $R_{\bar{c}}$ to 40×10^6 results in an attached flow pressure distribution.

5. Validate vortex theories for simple and mixed flow fields (panel, Euler, and Navier-Stokes techniques).

6. Provide additional vortex flap applications at transonic and supersonic speeds.

7. Investigate multiple vortex interactions. An example is shown in figure 25 for the B-1 airplane at M = 0.98 and $\alpha = 7°$. The flight vehicle experienced wing oscillations while in a windup turn (ref. 105). A wind tunnel model confirmed these oscillations and that they were due to two corotating vortices on the wing panel.

8. Study vortex interactions with inlet and exhaust flow fields.

9. Evaluate canard and strake effects on vortex flap design.

10. Expand theory and experimental data base for vortex breakdown. An example is shown in figure 25 for an F-18 water tunnel model (ref. 106). The vertical tails operate in the very turbulent flow field downstream of the vortex burst, which has led to tail oscillations and premature tail fatigue.

CONCLUDING REMARKS

This paper provides some background information for the Vortex Flow Aerodynamics Conference and resulted in the following observations:

Current slender wing airplanes do not use variable leading-edge geometries to improve drag polar for transonic maneuver conditions.

A large subsonic data base for the vortex flap concept has been generated; transonic and supersonic generic studies have started.

There is a need for validated flow field solvers for calculating vortex/shock interactions at transonic and supersonic speeds.

Many important research opportunities exist to theoretically and experimentally investigate fundamental vortex flows and apply that knowledge to analyze and design advanced fighter concepts.

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TABLE I.- SYMBOL DEFINITION OF DATA PLOTTED IN FIGURE 1
(OBTAINED FROM REFERENCES 5-8)

(a) Fixed Sweep

Symbol	Airplane	Λ_{LE},deg	A	Variable LE Geometry Used to Improve Drag Polar
⌂	F-15A	46	3.0	No
◊	F-16A	40	3.2	Yes
◇	F-4E	51	2.8	Yes
⌂	Viggen	55*	2.5	No
◺	F-106	60	2.1	No
◺	F-16XL	66.5*	1.62	No
△	MIG 21	57	2.2	No
◇	KFIR	61	1.86	No
□	Mirage 2000 and 4000	60	2.0	Yes
▽	Mirage III	61	1.94	No
▽	Mirage F-1	47.5	2.8	Yes
▽	Sepecat Jaguar GR-1	44	3.1	Yes
▷	F-5E	32	3.82	Yes
◁	F-20[1]	32	3.82	Yes
◁	F-18A	26	3.52	Yes
▽	A-4F	41	2.91	Yes
□	A-6E	29	5.31	Yes
◇	A-7D	40*	4.0	Yes
◁	MIG 25	39*	3.5	No
▷	SR-71	60	1.72	No
◺	Super Etendard	48	3.2	Yes
▷	SU-15	49*	3.1	No
◇	B-70	65.6	1.74 Undeflected tip	No
		70.8*	1.14 Deflected tip	No
D	Concord	67.5*	1.93	No

(b) Variable Sweep

Symbol	Airplane	Λ_{LE},deg	A	Variable LE Geometry Used to Improve Drag Polar
○	F-111F	16 → 72	7.6 → 1.6	Yes (low Λ_{LE})
▽	B-1B	15 → 67.5	9.6 → 3.1	Yes (low Λ_{LE})
◇	MIG 23/27	16 → 72	7.3 → 2.4	Yes (?)
◇	F-14A	20 → 68	7.3 → 2.6	Yes ($20° < \Lambda_{LE} < 50°$)

*Effective LE sweep angle (defined in figure 1)

[1]Preproduction airplane

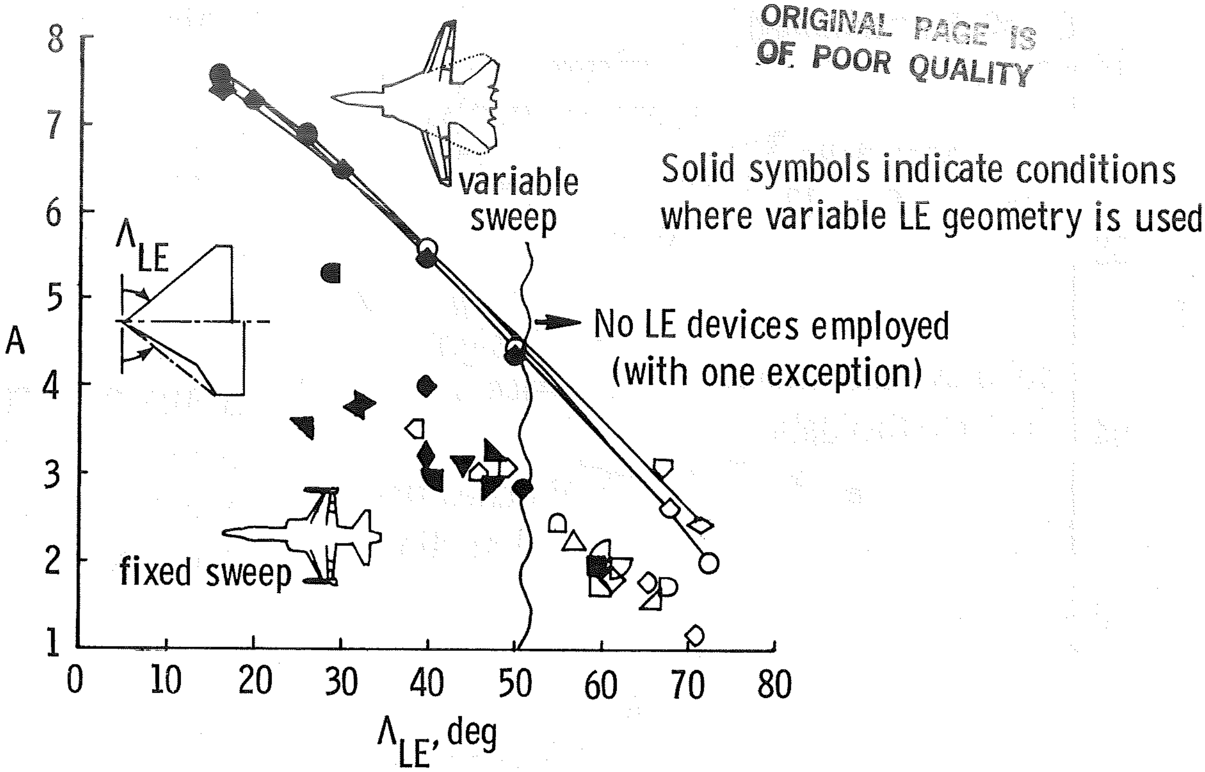


Figure 1.- Aircraft that use variable leading-edge geometry to improve maneuver drag polar. (See Table I for symbol definition.)

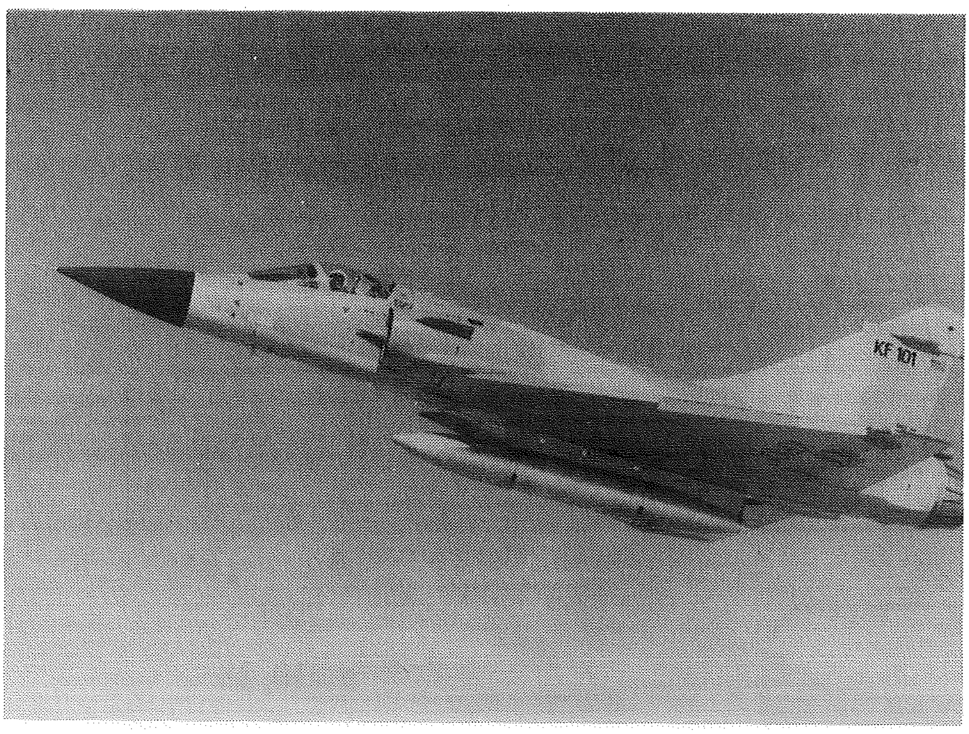


Figure 2.- Photograph of Dassault-Breguet Mirage 2000 with variable leading-edge flaps. (From ref. 9.)

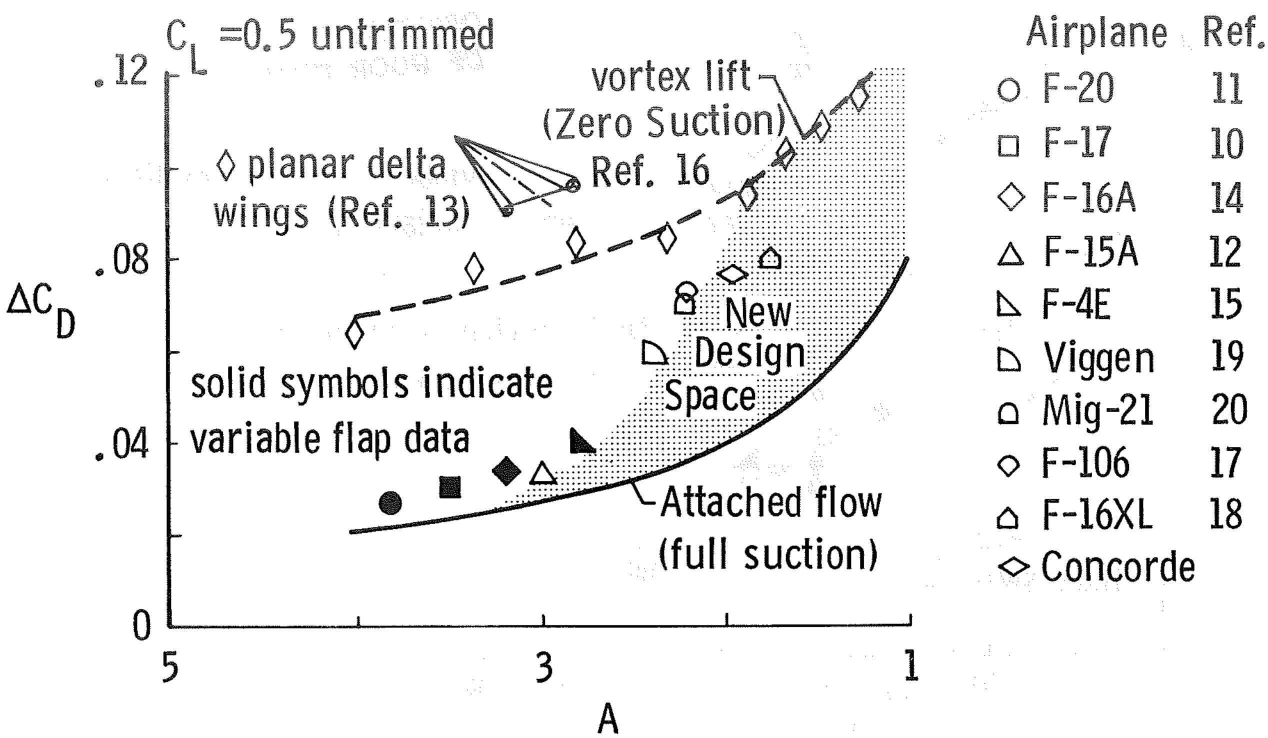


Figure 3.- Subsonic drag due to lift as a function of airplane model aspect ratio.

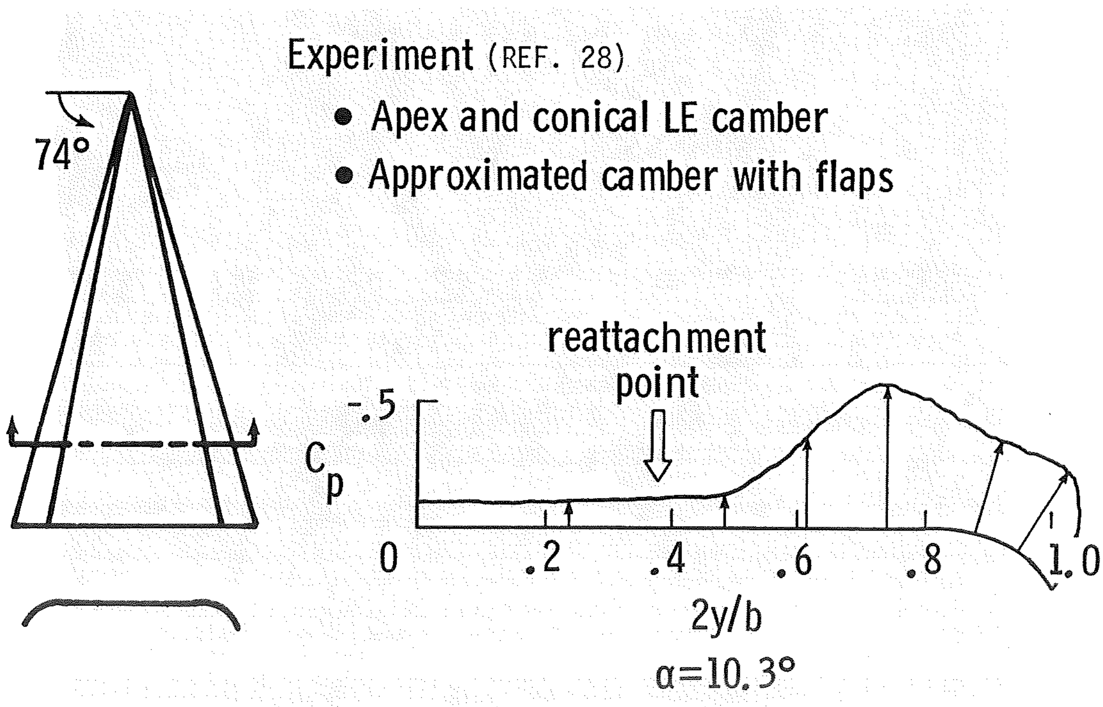


Figure 4.- Experimental investigation combining leading-edge camber on 74° delta wing with vortex flow. (From ref. 28.)

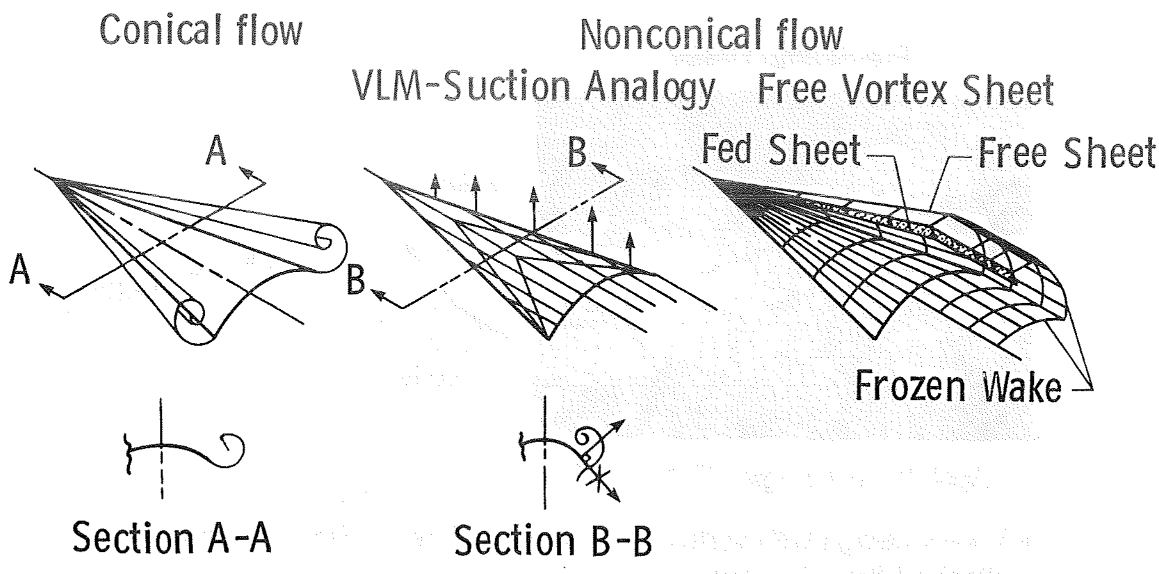


Figure 5.- Status of vortex theories for nonplanar wings in 1978. (From ref. 29.)

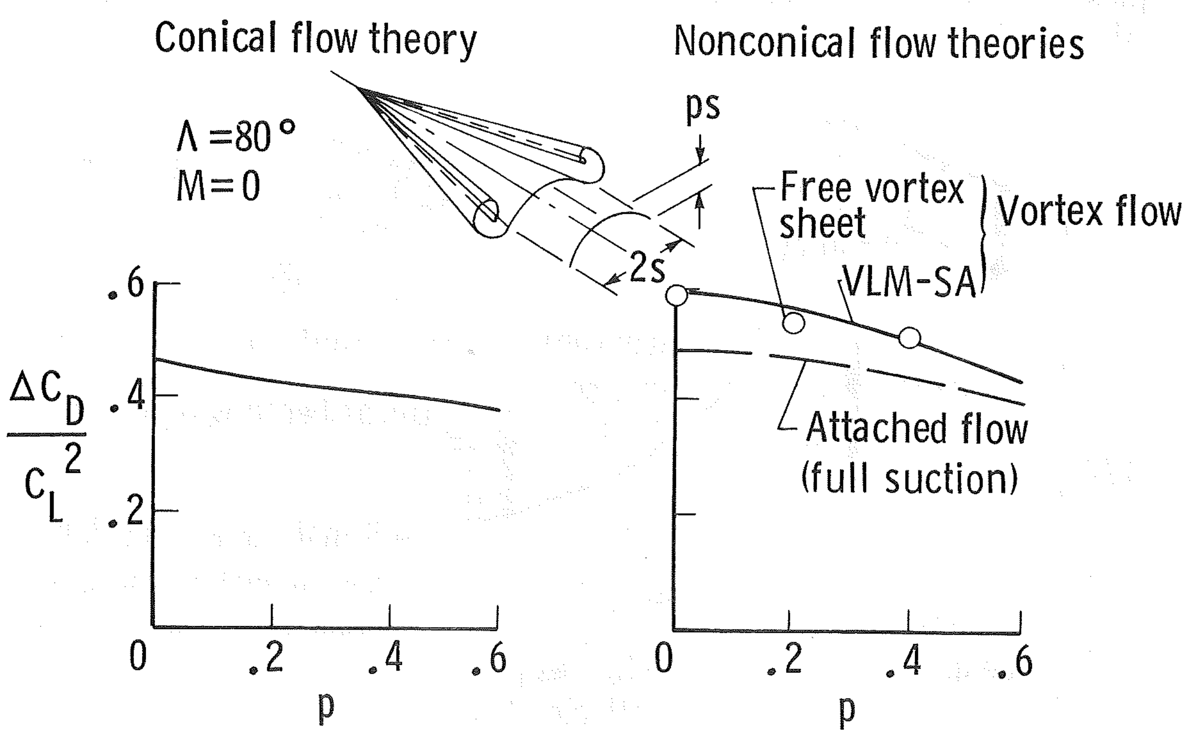


Figure 6.- Theoretical effect of camber height on drag factor. (From ref. 23.)

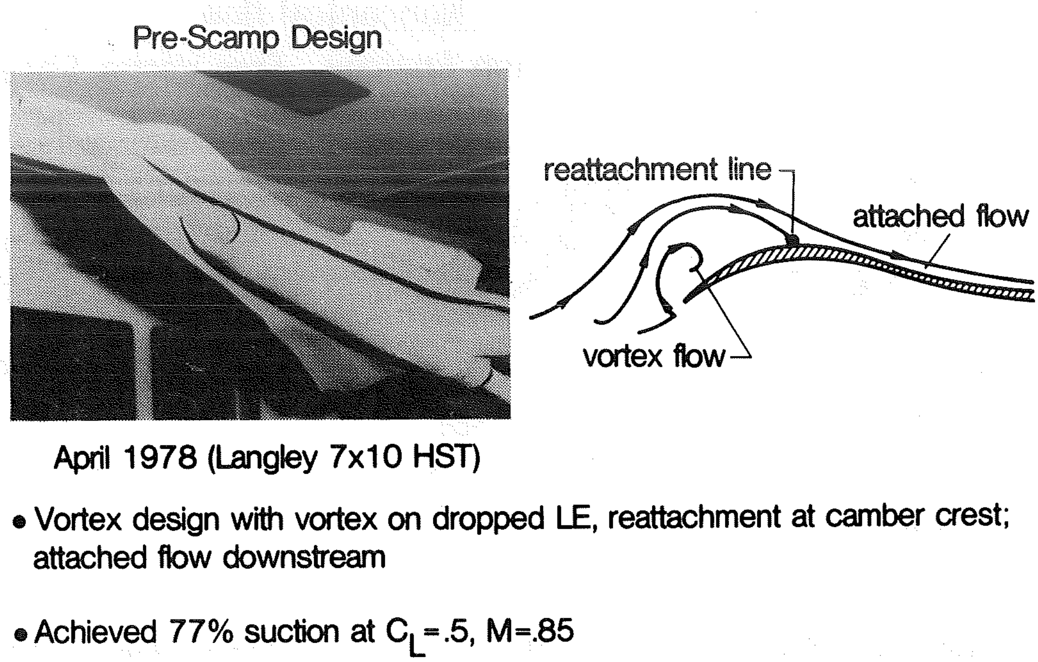


Figure 7.- Transonic maneuver vortex design for the Pre-Scamp configuration. (From ref. 35.)

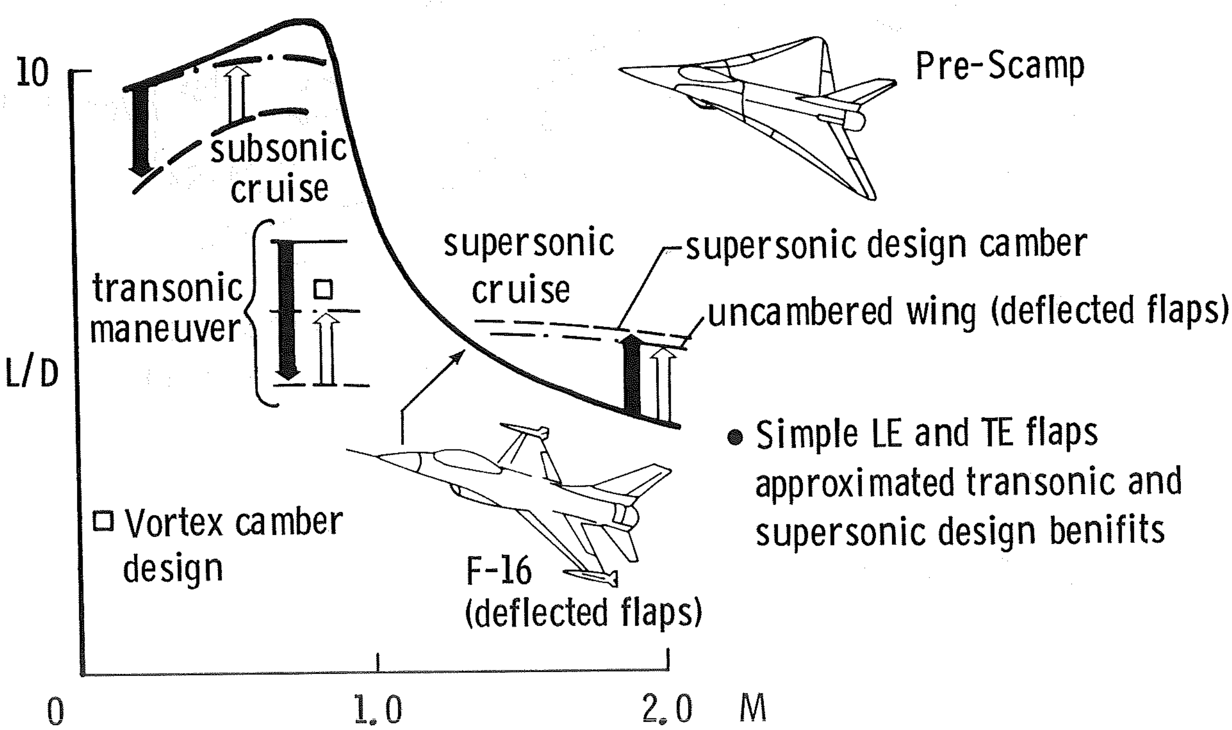


Figure 8.- Effect of sweep and articulated flaps on cruise and maneuver performance. (From ref. 37.)

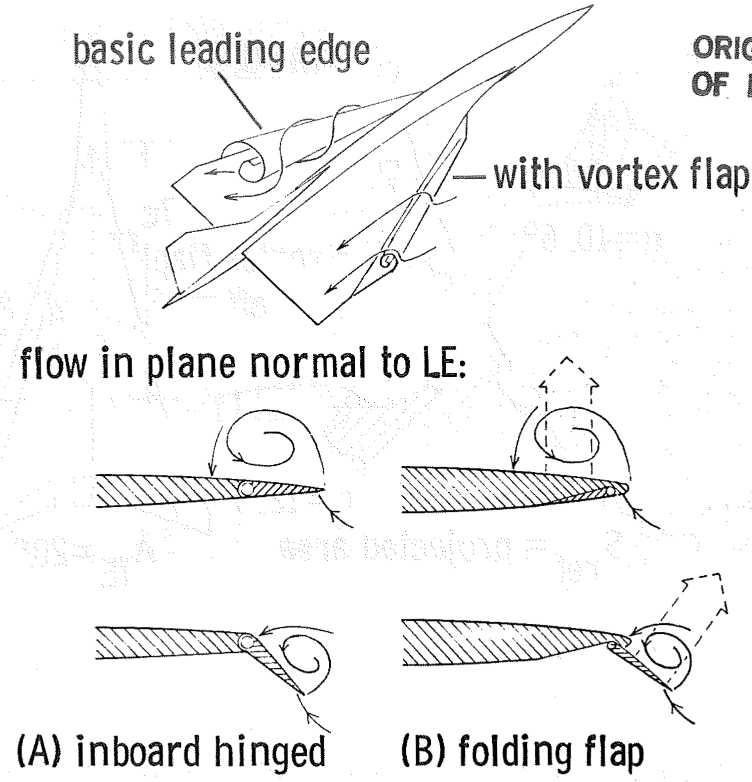


Figure 9.- The vortex flap concept. (From ref. 40.)

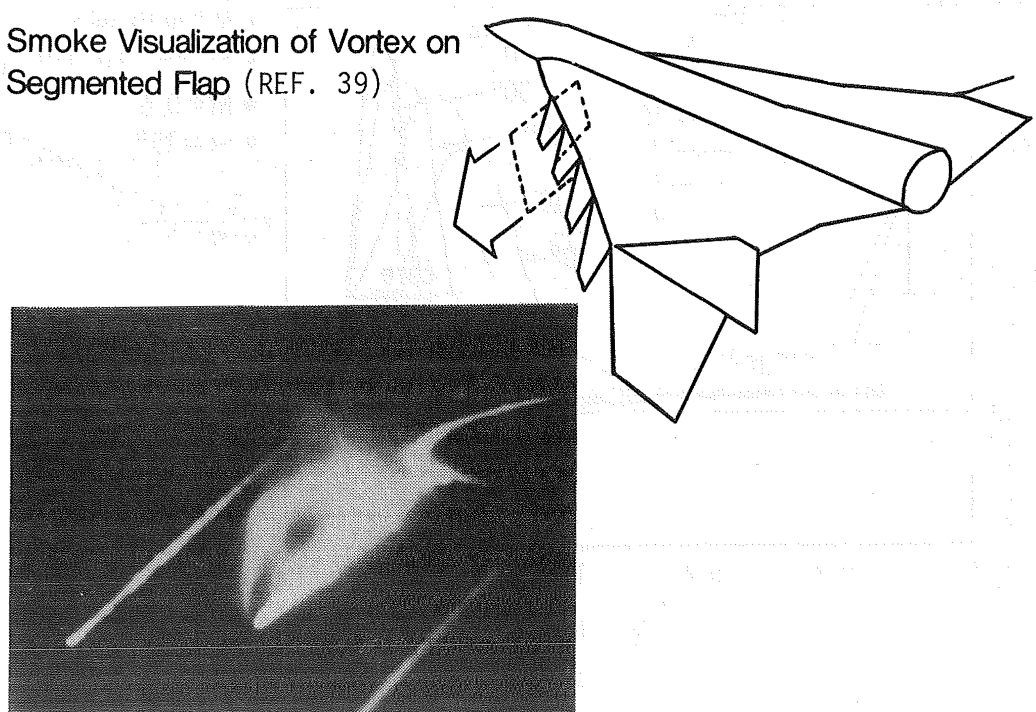


Figure 10.- Studies explore vortex flap hypothesis. (From ref. 39.)

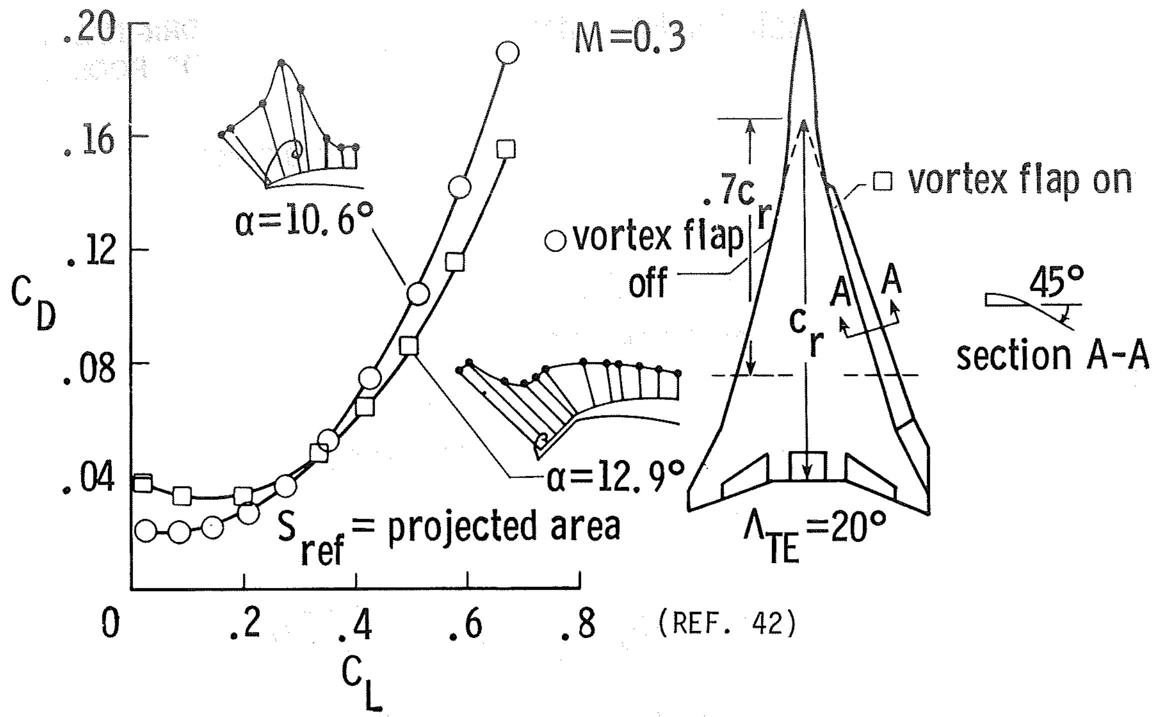


Figure 11.- Drag polar for vortex flap applied to an NASA/Boeing fighter model. (From ref. 42.)

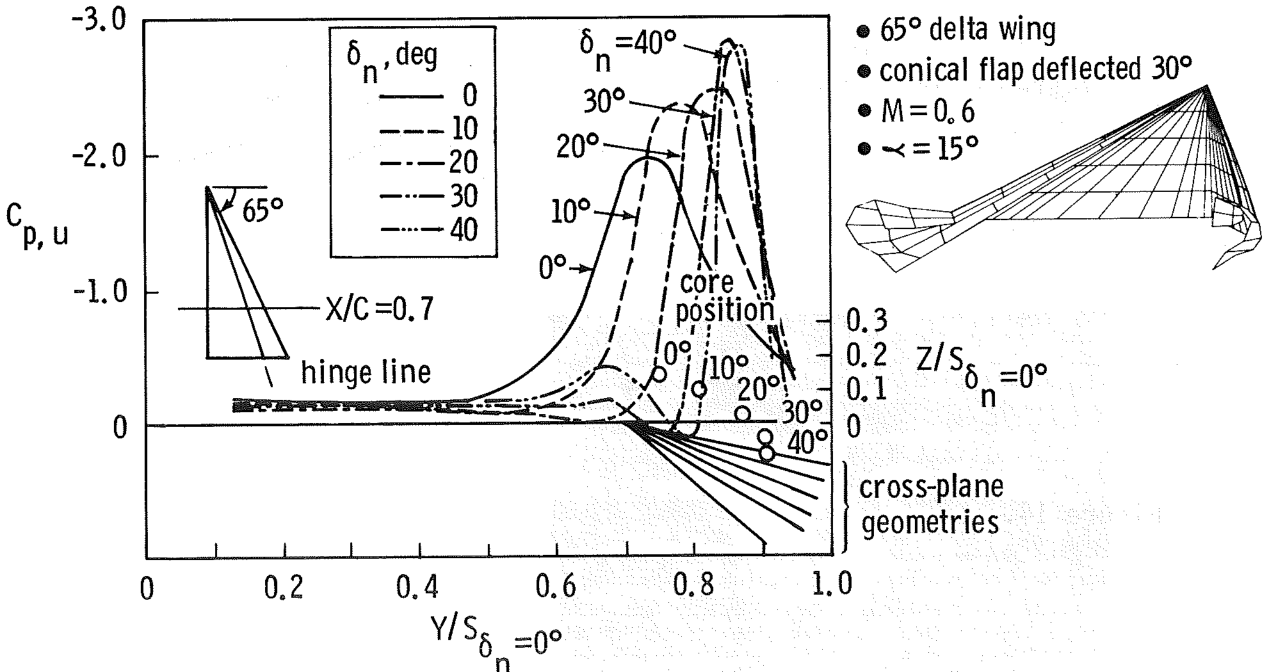


Figure 12.- Free Vortex Sheet analysis study of vortex flap pressure distributions. (From ref. 64.)

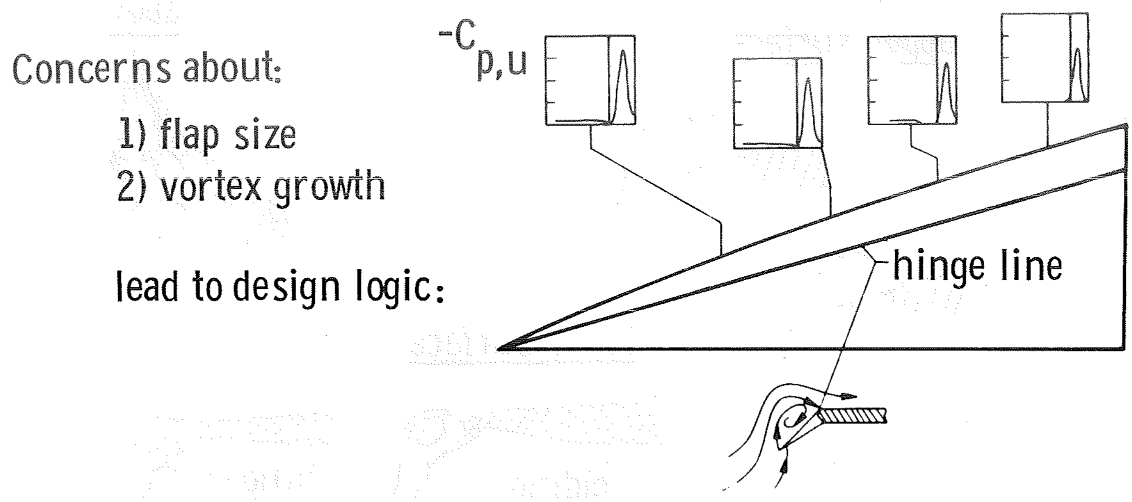


Figure 13.- Vortex flap design procedure. (From ref. 66.)

- Large Subsonic Data base
  - pressures
  - hingemoments
  - performance
  - stability and control
  - flow field diagnostics
- Basic Flap
  - flap planform, hinge line sweep
  - flap deflection
  - flap and wing aero section
- Alternate Flaps

Figure 14.- Status of current vortex flap studies at subsonic speeds. (From ref. 69.)

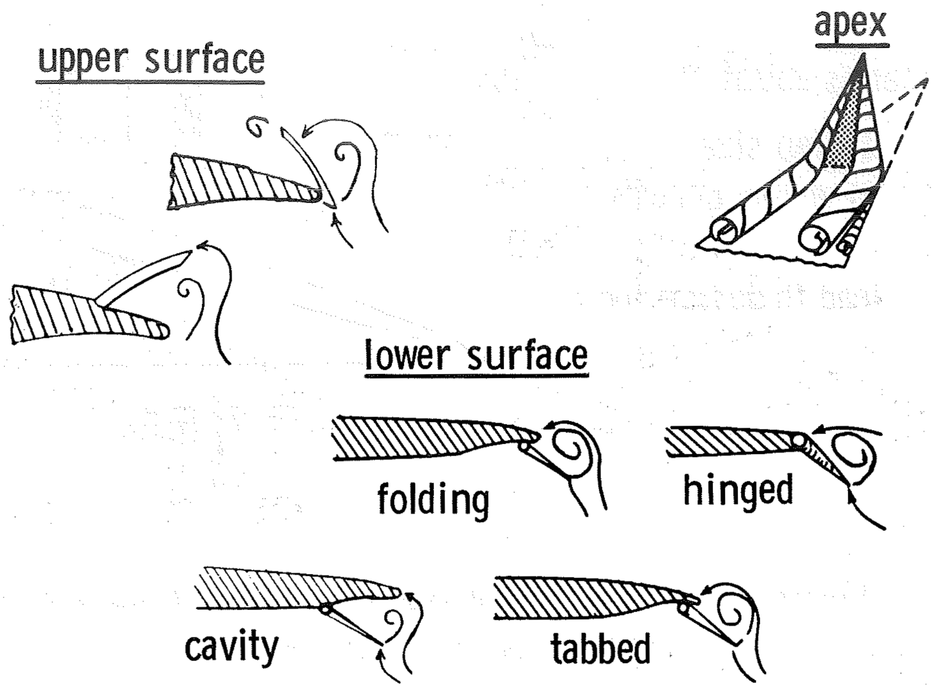


Figure 15.- Types of vortex flaps. (Adapted from ref. 37.)

- Concept is maturing subsonic
  - Experiments in concert with analysis and design theories
  - Applications to generic and aircraft models
  - Flight experiment being considered on F-106

Figure 16.- Summary of subsonic vortex flap studies.

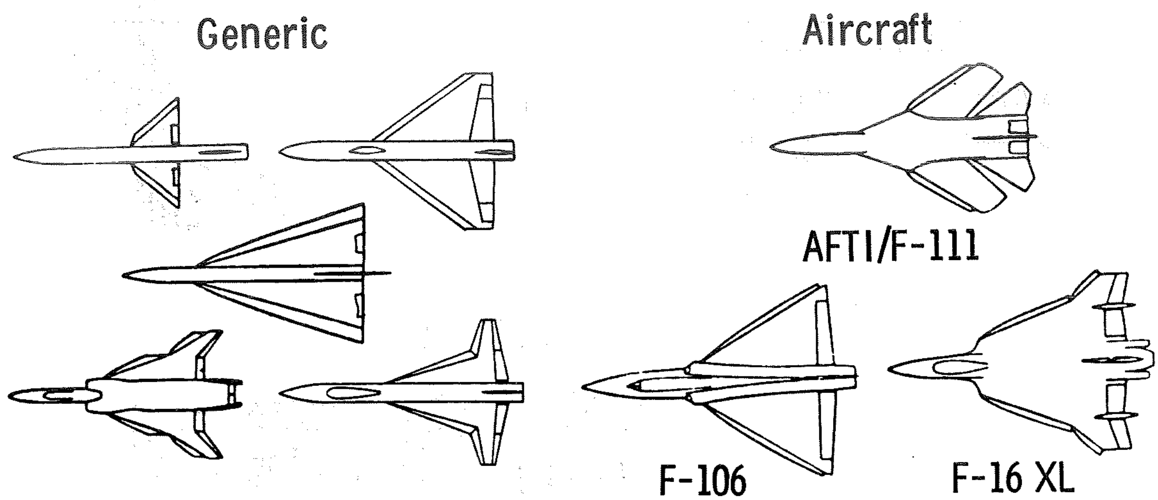


Figure 17.- Current configurations to which vortex flaps have been applied. (Updated from ref. 69.)

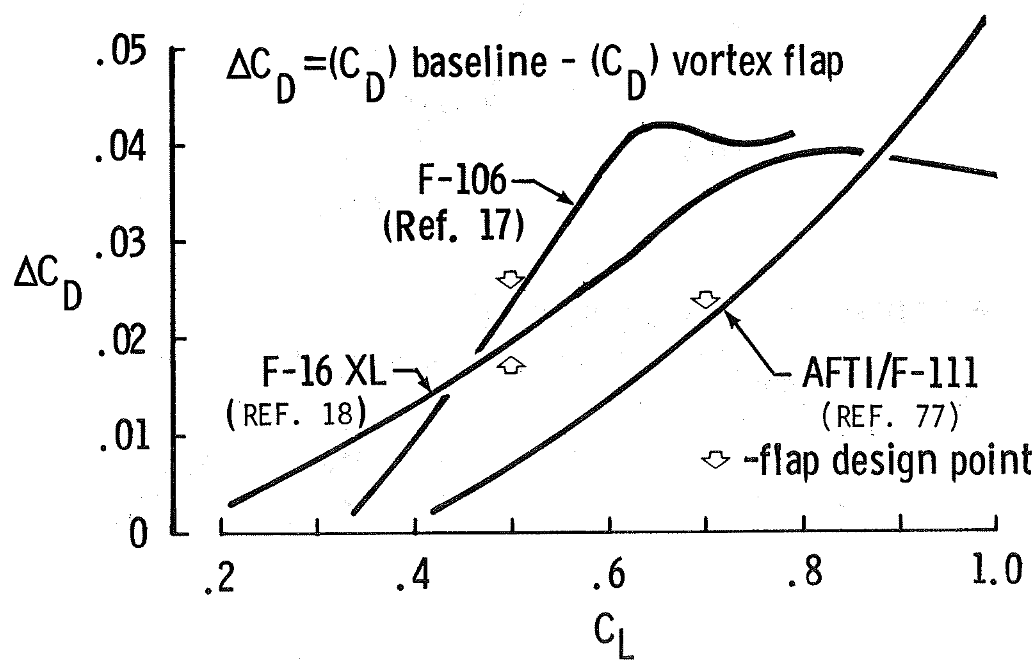


Figure 18.- Effect of vortex flaps on subsonic drag reduction; M = 0.6. (From ref. 69.)

- Generic studies have started
- Preliminary analysis tools are being validated
- Need additional codes to analyze vortex / shock interactions

Figure 19.- Status of current vortex flap studies at transonic and supersonic speeds.

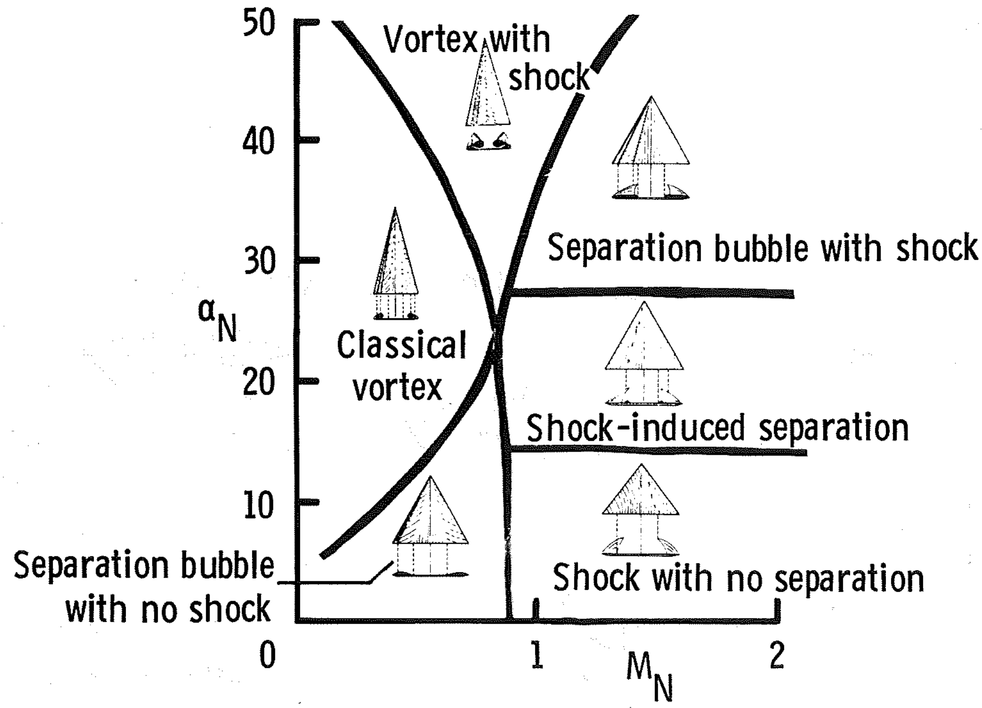


Figure 20.- Leeside flow over planar delta wings at supersonic speeds. (From ref. 81.)

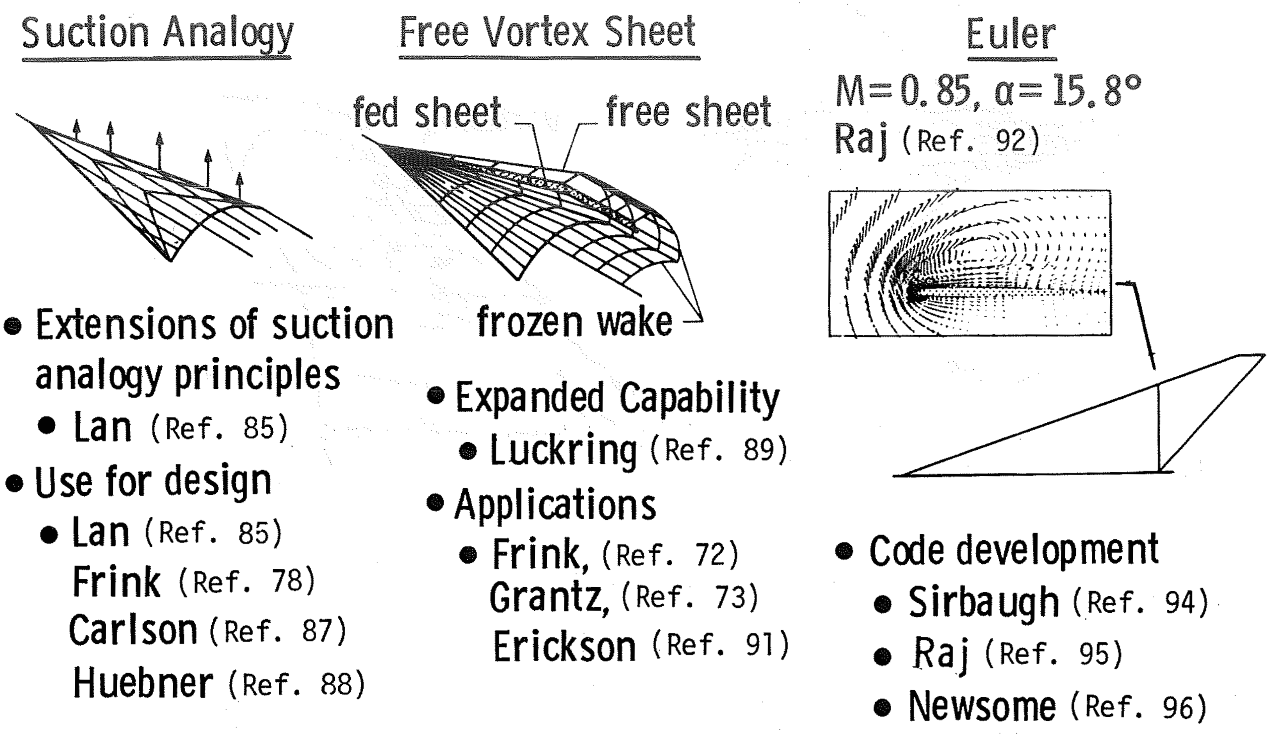


Figure 21.- Progress in inviscid leading-edge vortex theories.

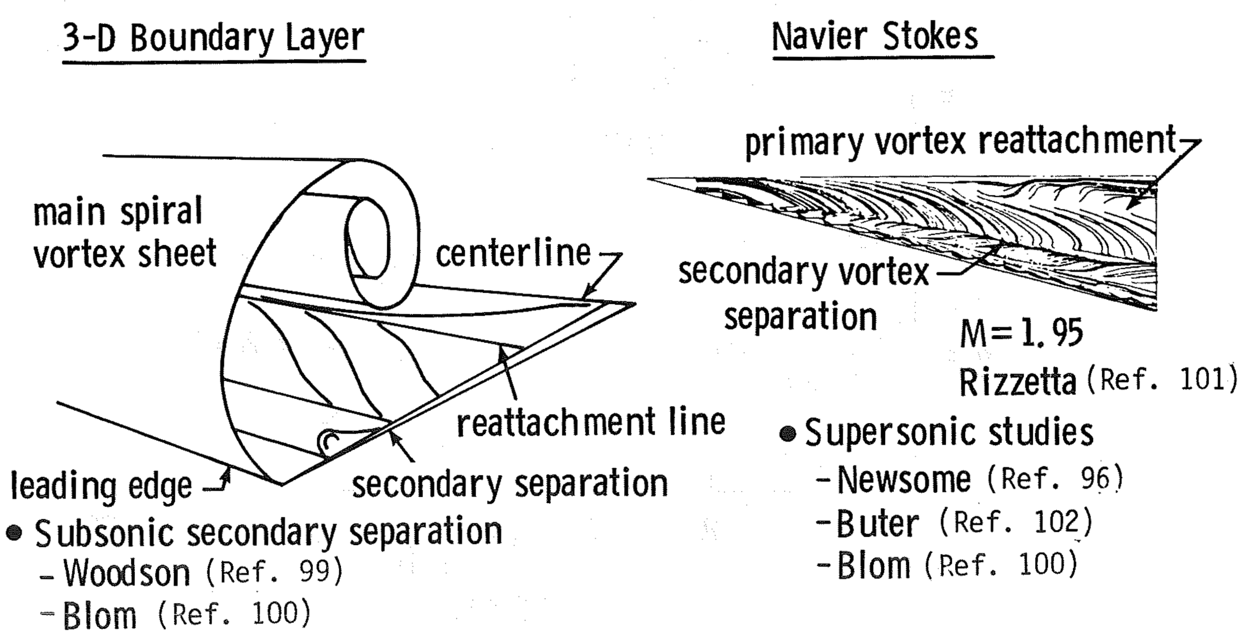


Figure 22.- Progress in viscous leading-edge vortex theories.

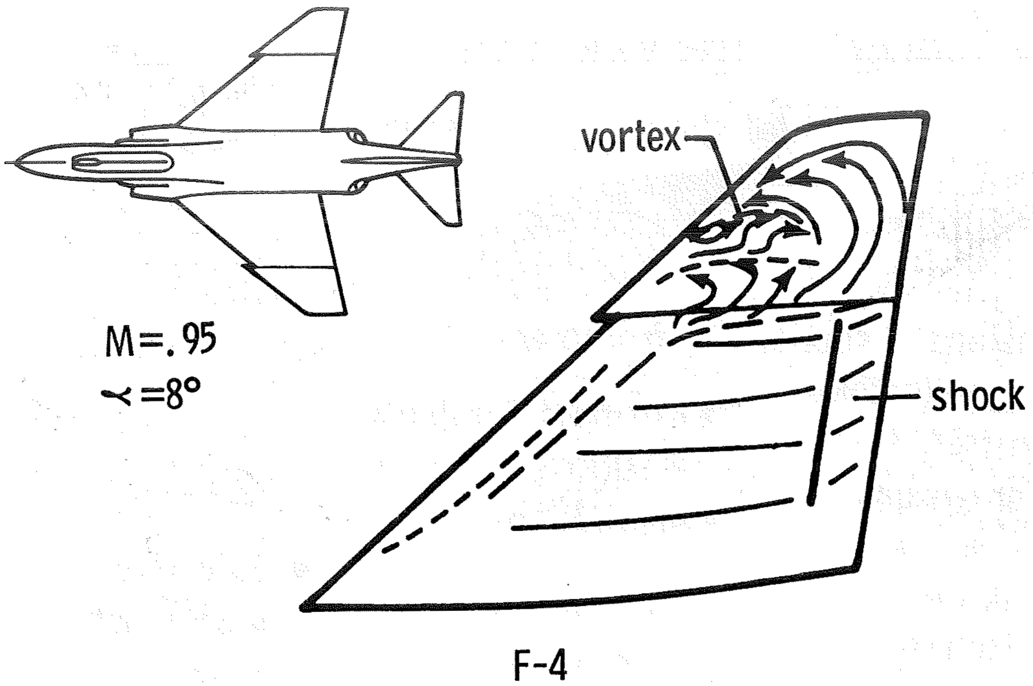


Figure 23.- An opportunity for research of vortex/shock interaction. (From ref. 103.)

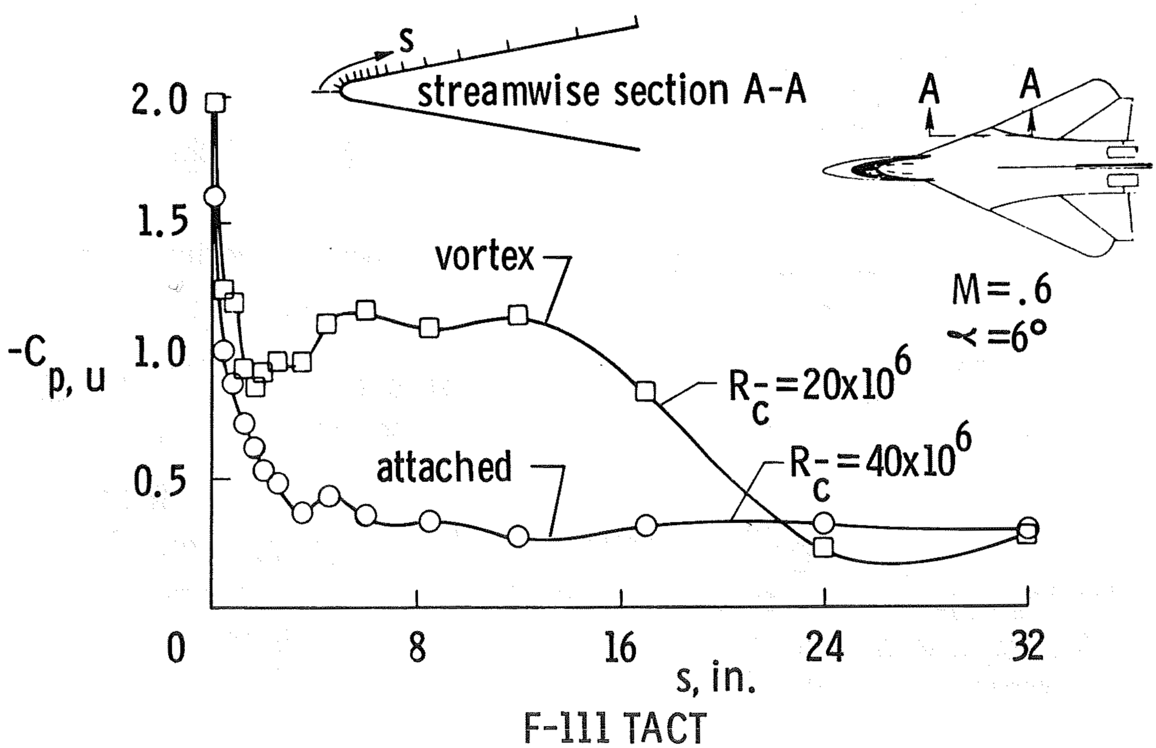
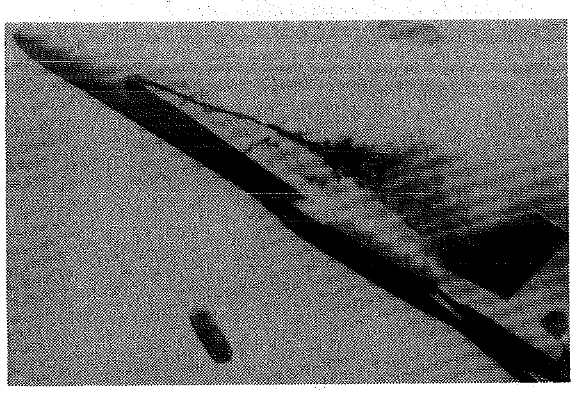


Figure 24.- An opportunity for research of the vortex development on a round leading edge. (From ref. 104.)

Vortex Burst



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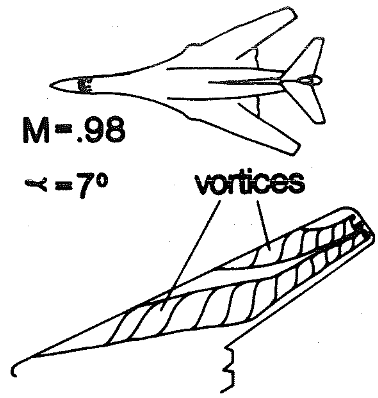
Multiple Vortex
Interactions



B-1

Figure 25.- Opportunities for research of vortex burst (from ref. 106) and multiple vortex interactions (from ref. 105).