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Wright Brothers Lectureship in Aeronautics

Applying Slender Wing Benefits to Military Aircraft

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Introduction

I AM deeply honored to have been invited by the AIAA to participate in this annual recognition of the great accomplishments of the Wright brothers It has been 80 years since their epoch flight, yet our appreciation of their genius continues to grow In addition to their design and engineering feats, they established solid scientific approaches in several areas of aeronautical research For example, in my own field of aerodynamics, the Wright brothers developed experimental equipment and test techniques, and carried out fundamental systematic studies, using some 200 models, covering the major parameters in airfoil and wing design In fact, much subsequent aerodynamic research can be considered as extensions and refinements of their approaches [1]

Therefore, in keeping with the spirit of the Wright brothers research and design accomplishments, as well as the scope of this meeting, I have elected to review some of the aerodynamic research performed at the Langley Research Center related to the application of slender wing benefits in the design of high-speed military aircraft In the context of this paper, slender wing benefits refer primarily to the supersonic performance and leading edge vortex flow associated with very highly sweptback wings Following a review of some early slender wing research, the paper presents several case histories of Langley contributions to the development of aircraft incorporating slender wing benefits and then summarizes some vortex flow technology that may contribute to future aircraft

Towards Slender Wings

Beginnings in Germany

As we look back over the 80 years that have passed since the Wright brothers epic flight, we find that at the halfway point, 40 years ago, an event took place in Germany that might be considered the beginning of the development of modern classical swept wing jet aircraft and the trend toward the slender wings of interest in this paper It was in December 1943 that the highly secret Me 262 project[2] was elevated to the top production priority in the German war effort In April of the following year, allied air forces began to encounter squadrons of the world's first operational jet aircraft Jet aircraft, of course, were not new. Prototypes had been built and flown previously by the Germans, British, and Americans However, a surprising feature of the Me 262 was its sweptback wing which contributed to a speed advantage through a delay of the onset of compressibility drag—a benefit of sweep not understood in the allied nations at the time Thus, the Me 262, shown in Fig 1, became the world's first swept wing jet aircraft Although its 18 deg of sweep back was the fortuitous result of a 1940 design change to fix a center-of gravity problem, that same year German researchers had demonstrated in the wind tunnel[3] that Busemann's 1935 supersonic swept wing theory[4] also applied to subsonic compressibility effects Advanced versions of the Me 262 incorporating more highly swept wings were studied with wind tunnel tests of a 40 deg version beginning in 1941 It reached the prototype stage in early 1945 but was accidentally destroyed before its first flight [5] After the war, the fairly extensive wind tunnel data were used in the conversion of the North American F 86, during its design stage, to a sweptback wing [6] Another version of the Me 262 was a 1945 design project for a night fighter having a 50 deg sweptback wing [7]

Although not strongly pursued because of many practical considerations of the time, the slender delta wing was being investigated in Germany for supersonic applications The best known work was that of Lippisch,[8] designer of the Me 163 rocket propelled tailless delta wing prototype

Early Langley Research

I joined the aerodynamic research staff of NACA's Langley Research Center in July of 1944, shortly after allied pilots had first encountered the swept wing Me 262 However, the benefit of sweep with regard to high speed flight remained a mystery outside of Germany until January 1945, when R T. Jones of the Langley Research Center completed a theoretical study [9] He demonstrated, independently of Busemann's work, that wing pressure distributions are determined solely by the "component of motion in a direction normal to the leading edge." He further pointed out that, for efficient supersonic flight, the wing should be swept behind the Mach cone with the sweep angle being such that the normal component of velocity is below the airfoil's critical speed While the subsequent acquisition of the German swept wing data played a role in dispelling doubts regarding the validity of Jones' theoretical work, it should be noted that G. S

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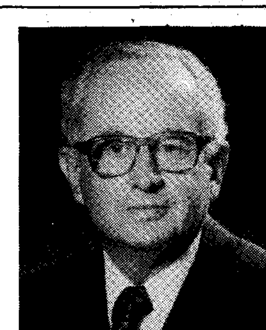

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Schairer of Boeing gives Jones "full credit for the XB-47 being built with swept wings "[10]

Another event of importance to slender wing applications occurred at Langley in 1946 when Wilson and Lovell[11] demonstrated, during tests in the full-scale tunnel, that the poor maximum lift of a slender delta wing was greatly improved by replacing the round leading edge with a sharp edge This change created the now well known separation induced and highly stable leading-edge vortex flow with its associated vortex lift A "cross-flow separation" model of the vortex flow was also proposed in their paper Although this research remained under a security classification for four years, it did stimulate research at Langley and Ames and interest in industry Much of the international interest in vortex flow was generated somewhat later through its independent discovery by French researchers during studies carried out in 1951 and 1952 [12]

Some consequences of the supersonic cruise and high-angle-of-attack subsonic flows associated with slender wings are illustrated in Figs 2 and 3 Regarding the relatively low lift coefficient supersonic cruise conditions with attached flow, Fig 2 illustrates the reduction of supersonic lift-dependent drag as the leading edge is swept behind the Mach cone, thus providing a subsonic type flow with upwash manifesting itself as a thrust component potential that more than offsets the adverse effect of aspect ratio reduction For the thin wings desired for supersonic aircraft, this thrust, in effect, is provided by use of camber and twist to maintain attached flow For the case of $M=2\ 5$, a leading-edge sweep angle in the 70 75 deg range is required for minimum drag

For the higher angles of attack of interest at subsonic speeds, the vortex-type flow forms, and the resulting large lift increments are illustrated in Fig 3 This lift, associated with the large mass of air accelerated downward by the nonplanar vortex sheets, greatly relieves the lift deficiency of slender wings having attached flow The vortex induced reattachment also avoids the undesirable trailing-edge separation and the attendant stall characteristics that often plague conventional swept wings Also beneficial is the nonlinear aspect of the vortex lift, which allows the low gust response of slender wings in the low angle-of-attack range corresponding to sea-level dash conditions to be realized, while still providing high levels of lift for takeoff, landing, and maneuvering

The vortex flow concept, of course, does suffer from the drag associated with the absence of leading edge thrust. This problem is reduced to some extent by the smaller angles of attack required and by the use of various vortex compatible leading-edge devices Fundamental, however, to the slender wing is, of course, the reduced subsonic cruise efficiency associated with the low aspect ratio

Some Application Concepts

Several supersonic military aircraft having relatively slender wings were developed during the 1950's These were compromise designs to provide reasonable subsonic cruise efficiency Beginning in the 1960's, concepts which more completely utilize slender wing benefits were developed Two general classes are illustrated in Fig 4

One class is the variable sweep wing concept Primarily an attached flow concept, it allows full benefit of slender wing supersonic performance and low altitude penetration capabilities, while maintaining the many benefits of the classical high aspect ratio subsonic wing This provides broad multi design-point capabilities In the other class are the fixed planform "hybrid" wings which utilize both slender and nonslender wing panels These wings combine attached flows and vortex flows in various combinations to provide some degree of multi-design point capability without resorting to variable sweep Two subclasses of hybrid wing concepts are illustrated: one which uses vortex-lift strakes and is biased toward transonic maneuvering, and the other a slender cranked wing biased toward supersonic cruise.

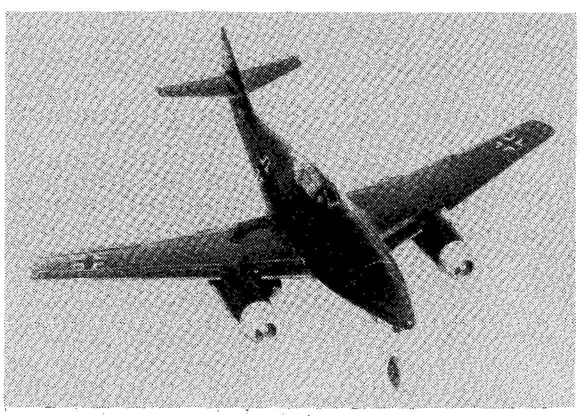

Fig 1 Messerschmitt Me 262—the first swept wing jet.

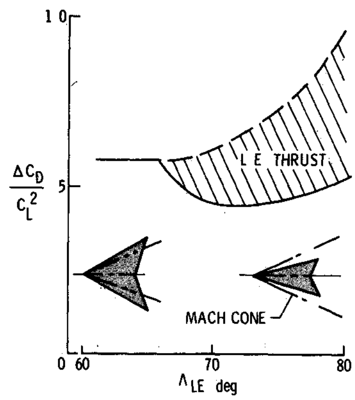

Fig 2 The benefit of slender wings on supersonic lift dependent drag; $M=2\ 5$ with attached flow

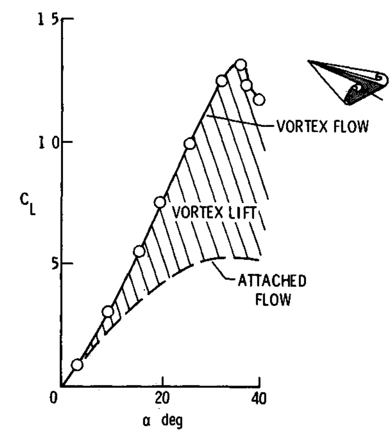

Fig 3 Slender wing vortex lift benefit at low speed; $\Lambda_{le}=75$ deg

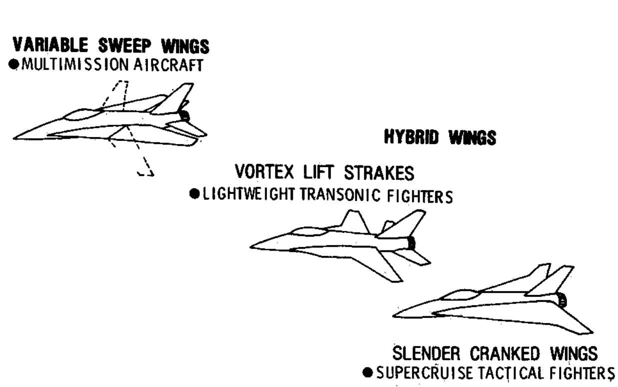

Fig 4 Some applications of slender wing benefits

The following two sections will review some case histories of Langley aerodynamic research contributions in relation to the development of military aircraft utilizing these concepts

Variable-Sweep Wings

Early Research

Once the incompatibility between efficient subsonic and efficient supersonic wing designs was recognized, aerodynamicists and designers began considering in-flight variable sweep as a means of reducing the compromises of a fixed sweep design.[13] The Germans considered several types of variable sweep near the end of World War II but, for practical considerations of that time, did not pursue them

The first wind tunnel studies of variable sweep concepts appear to be those conducted at the Langley Research Center in 1946 The first dealt with the variable oblique wing concept, and the low-speed flying qualities were investigated in early 1946.[14] Although somewhat promising, the results did not create an immediate interest in oblique wing aircraft. However, several people in the U S. had thoughts of developing a research airplane with in-flight variable sweep capability to evaluate the mission advantages of symmetrical variable sweep One was C J Donlan of Langley who, during the latter part of 1946, initiated what is believed to be the first wind tunnel study of the symmetrical variable sweep concept. Using a single pivot on the centerline, the study, reported by Donlan and Sleeman,[15] established the magnitude of the increase in longitudinal stability as the sweep was increased—a source of high trim drag and reduced maneuverability—and explored several aerodynamic approaches to the problem It was concluded that some type of fore and aft translation coordinated with the sweep changes, although undersirable from a weight and complexity standpoint, would probably be required

Following this research, Langley and the Bell Company considered an in-flight variable-sweep version of the Messerschmitt P 1101 design [13] This became the Air Force/NACA X-5 research airplane which first flew in 1951 In the following year, the Navy-Grumman XF10F began flight tests. Both aircraft utilized fore and aft wing translation coordinated with sweep and encountered no problems with the sweep mechanisms except that the translation feature added considerable weight and bulk These aircraft demonstrated many of the advantages of variable sweep but, in both cases, the planned engines were never received, thereby precluding demonstrations of the supersonic advantages [13,16]

Joint Program with the United Kingdom

At the conclusion of flight activities of the X 5 and the XF10F, military interest in variable sweep was at a low ebb. With little hope that supersonic flight could be achieved for more than brief dashes, and with aerodynamic "fixes" alleviating some of the swept-wing problems, a moderately swept fixed-geometry compromise seemed acceptable However, some interest was maintained at Langley as a result of Donlan's intuitive belief that variable sweep could be attractive in relation to future military requirements In the latter half of 1950 such requirements began to emerge

By 1957 both the British and the U S Navy had become interested in a strike fighter with low altitude high-speed capability In this same period, industry and NACA studies indicated that sustained supersonic flight was feasible but, of course, would require higher sweep angles which would further aggravate takeoff and landing problems. Thus, with the need for slender wings to meet the emerging supersonic cruise and low-level penetration requirements, and a growing interest in the multimission concept, variable sweep began to generate renewed interest at Langley.

The British also had maintained some interest in variable sweep, and in 1958 they sought NATO aid to continue studies of Barnes Wallis' conceptual design of a supersonic transport, or bomber, known as the "Swallow " At the suggestion of John Stack, an associate director of Langley and a member of the mutual weapons development program steering group of NATO, a description of the Swallow was sent to Langley for review Following the review, Donlan recommended NACA support but suggested that consideration be given to tactical missions incorporating low level high speed dash

The Initial Program

In November 1958 a joint program was arranged[13] which included Langley tunnel tests of the configuration series, shown in Fig 5, consisting of the "Swallow" and three Langley concepts

The "Swallow," designated as configuration I, was a tailless aircraft with a slender arrow wing having 80 deg sweep A unique system of pivoting engine nacelles and pylons was to provide control for the aircraft Severe aerodynamic problems were encountered, particularly in the stability and control area In view of this, the mechanical complexity, and the Langley interest—soon shared by the British—in tactical-type aircraft, tests of the Swallow were soon terminated However, there is little doubt that Wallis' work contributed to the renewed interest in the United States

The Langley configurations placed the engines in the fuselage of somewhat conventional wing body tail arrangements Emphasis was placed more on tactical-type aircraft Configurations II and III utilized wings having planforms somewhat similar to the Swallow but mounted on a conventional fuselage with the wing pivots at the edge of the fuselage These two concepts utilized combinations of folding tails, canards, and elevons as possible means of reducing the undesirable longitudinal stability changes with wing sweep variation, while maintaining adequate longitudinal control power. However, the folding tails provided insufficient control of the aerodynamic center shift and other control problems were encountered

Although somewhat discouraging overall, the results for the first three configurations indicated some benefits of various fixed-geometry lifting areas located ahead of the pivoting wing panels in reducing the aerodynamic center shift and provided guidance in other areas

An Emerging Solution

At this point, an attractive solution began to emerge as additional conceptual studies of the overall characteristics were combined with a theoretical, parametric study related to the aerodynamic center travel The theoretical study indicated that if the pivot was strategically located outboard of the fuselage, the desired span variation with sweep could be obtained with a considerably reduced aerodynamic center shift This resulted from a combination of reduced geometric shift of the outer wing panel and a greater shift of lift from that panel to the fixed panel as sweep increased This solution would allow a conventional arrangement of horizontal and vertical tails, and avoid the additional variable-geometry features of the other configurations Based on these studies and the subsequent tunnel tests, United States patents were awarded to Toll for a strategic aircraft concept[17] and to Alford and Polhamus for a tactical aircraft concept [18]

The tactical aircraft concept was added to the program (Fig 5) as configuration IV As with the other Langley designs, it was an engine-in fuselage arrangement However, the wing pivot was located outboard of the fuselage and the canard and folding aft tails were replaced by a conventional tail deflected symmetrically for pitch control and differentially to augment the roll control provided by the wing ailerons These features, in general, are incorporated in the large number of variable sweep aircraft throughout the world today

Tests of configuration IV confirmed its expected advantages. The low-speed results for the four configurations were published by Alford and Henderson,[19] and it was concluded that configuration IV offered a promising design approach. Research was extended into the transonic range by Alford et al.,[20] and to supersonic speeds by Spearman and Foster.[21] No serious problems occurred, and it appeared that, with the normal design refinements, the concept offered the potential of combining the supersonic cruise and low-altitude transonic dash benefits of the slender wing with the many subsonic benefits of the classical subsonic wing.

Expanded Langley Program

With the commitments to the British having been honored, and all of the results having been shared, Langley concentrated on expanding its tactical aircraft program. It was at this point that John Stack's role became decisive. A dynamic personality with a remarkable ability to recognize the potential of technical advances, he was well-known and highly respected throughout the aeronautical community With military aircraft requirements beginning to place more emphasis on low-altitude penetration and unrefueled ferry range, he stimulated interest in variable sweep at high levels in the services and industry and began to expand the program to provide the data for a solid design base.

One of the first studies was to provide additional wing design data, with regard to the longitudinal stability problem, on a more detailed configuration. The results are summarized in Fig. 6 where the aerodynamic center shift with wing-sweep angle is presented. Shown for reference is the large variation associated with a centerline pivot and the greatly reduced variation of the configuration IV concept. For the more detailed configuration, two wing designs which provided the same increase in wing span as the sweep was reduced were investigated. One wing (CAP I-A) had an outboard pivot and a large glove similar to configuration IV, and the other (CAP I-B) had a pivot at the edge of the fuselage and a small glove area. Wind tunnel results reported by Spencer[22] confirmed the benefits associated with the configuration IV type concept in the low-speed regime. Transonic and supersonic tests generally verified the anticipated performance advantage of variable sweep and the adequacy of the control concepts. This research and extensions to other aerodynamic technology areas (see summaries in Refs. 13 and 26) provided data for preliminary design tradeoffs.

Applied Research

Preliminary design and performance studies utilizing the research data indicated attractive multimission capabilities. By the end of 1959, both services were seriously considering variable sweep—the Navy for a carrier-based combat air patrol aircraft and the Air Force for a tactical fighter with extremely diverse requirements.

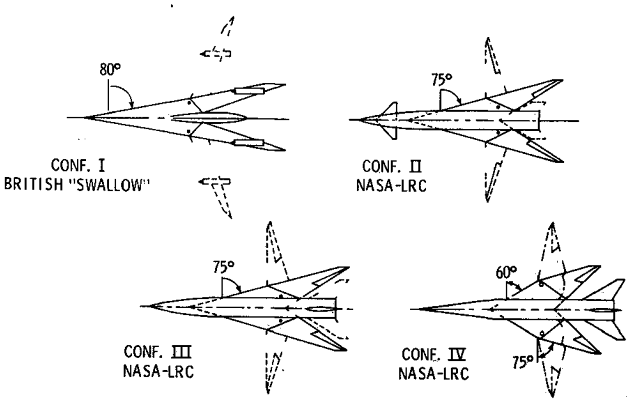

Fig. 5 Variable-sweep concept study.

Langley then embarked on an applied research program, under the overall technical direction of M. R. Nichols, assisted by D. D. Baals, to provide aerodynamic design data directly applicable to these requirements. The three-year program involved nearly every major wind tunnel facility at Langley and included configuration refinements in areas ranging, for example, from aerodynamic performance, to propulsion integration, to flying qualities. Space will not permit a review of the complete program. The reader is referred to the summary papers[23-26] and their references for an indication of the scope of the work and of the many researchers involved.

Some of the configurations studies are illustrated in Fig. 7 The first, referred to as CAP II, was directed to the Navy's combat air patrol mission and studied over the complete sweep and speed range by Spearman et al. While the Navy preliminary design needs generally were satisfied by the data obtained from the CAP I and CAP II configurations, the Air Force requirements raised a new challenge. In addition to combining STOL, high-altitude supersonic, and long-range subsonic capabilities; a supersonic, rather than high subsonic, on-the-deck penetration mission was required. This tended to drive the configuration toward a more slender wing and a long, high fineness ratio fuselage; thus a new series of configurations was designed and tested. Two in the series, designated TAC 7 and TAC 8, are shown in Fig. 7 All of the TAC series incorporated a fully folded wing concept for sea-level penetration to reduce wave drag, skin friction, and gust response. TAC 7 utilized pivots located at the edge of the fuselage, while TAC 8 utilized the outboard-pivot design. Although TAC 7 exhibited the problems with shift in aerodynamic center discussed previously, it was included to

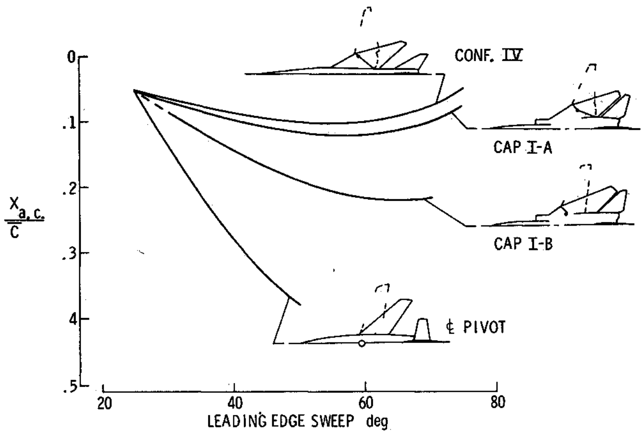

Fig. 6 Aerodynamic center shift with sweep.

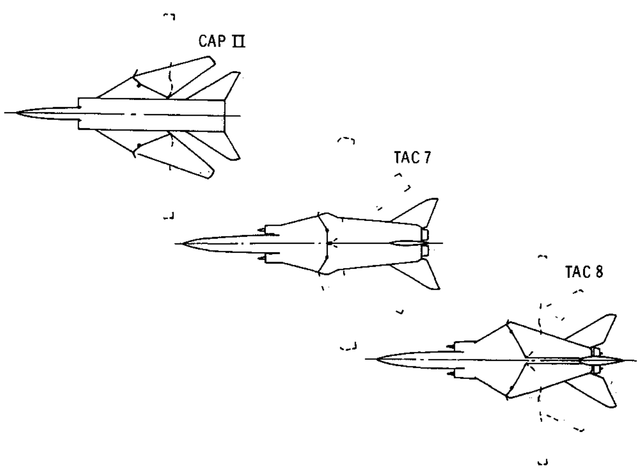

Fig. 7 Examples of applied research configurations.

provide tradeoff information relative to the new dash mission. The final configuration details, subsonic testing, and the critical transonic dash tests were carried out and reported by Bielat et al.[27]

The research was then extended over a wide range of Mach numbers and sweep angles to define the optimum sweep position for each leg of the various missions. In Fig. 8 (taken from Ref. 23), the aerodynamic efficiency parameter, L/D, is presented as a function of sweep angle for several Mach number and altitude conditions for the TAC 8 configuration at a weight of 60,000 lb. The benefits of variable sweep are readily apparent. For the subsonic ferry mission with the wing in the 25 deg sweep position, a lift-to-drag ratio in excess of 18 was obtained, and for the supersonic cruise the 75 deg sweep position is optimum. Also illustrated is the fact that, while the efficiency of sea-level supersonic dash is fundamentally very low, there is some L/D advantage for the fully folded wing concept for the dash. Reference 23 also illustrates the large reductions in gust response as the sweep angle is increased—an important consideration for the sea-level penetration. The TAC series was extended into the large number of technology areas mentioned earlier, and over 30 technical papers were published.[26] During this period, the research staff worked closely with the services and industry to assure maximum technology transfer and to assist through several cooperative programs.

Variable-Sweep Military Aircraft

The Langley variable-sweep research program played an important role in the development of the F-111, F-14, and B-1. These aircraft, which have successfully combined slender wing benefits with the benefits of the classical subsonic wing, are shown in Fig. 9 flying in their slender wing modes.

The General Dynamics F-111 was the world's first production variable-sweep aircraft. Although the abortive attempt to include the Navy requirements in the F-111 resulted in some design compromises related to the on-the-deck penetration mission,[13] the aircraft has provided outstanding multimission performance.

The Grumman F-14 has become the mainstay of the Navy and, as a single-service aircraft from the start, has been able to more nearly optimize the variable-sweep concept. With the wing pivots located well outboard to control the aerodynamic center shift, outstanding supersonic maneuverability has been achieved in the slender wing mode in addition to outstanding carrier operation and extremely long loiter capability in the wing's open mode.[16]

Interest in the B-1 was renewed recently as a result of Defense Department studies indicating it as the best near-term candidate for the next strategic bomber. In 1982, Rockwell received a development and production contract for the B-1B. It is, of course, the slender wing capability for low-altitude penetration, combined with the classical high-aspect-ratio wing for long subsonic unrefueled range, that makes the aircraft attractive as a strategic bomber.

Soon after the development of the F-111, variable-sweep aircraft began to appear in the Soviet Union and have almost completely dominated their supersonic aircraft development since that time.[16] In western Europe, the variable-sweep Tornado provides Great Britain, Germany, and Italy with their most advanced combat aircraft.

The experience gained from 25 years of variable-sweep aircraft development and operation has indicated it is a viable concept for providing slender wing benefits without sacrificing subsonic performance. Sweep mechanisms have been trouble free and their weight more than offset by the benefit of variable sweep on aircraft gross weight. Experience with the F-14 design, for example, indicated that the supersonic and carrier suitability requirements alone would have driven a fixed-planform aircraft to a much higher gross weight.

While the technology is in hand, future applications will depend, of course, upon the specific aircraft requirements. The opportunity still exists for a more complete understanding of the best way to exploit the concept, for example, the current study of the addition of variable camber for a more complete "mission-adaptive" wing. Also, the potential of several design approaches other than those in current use—such as the variable-skew wing and variable forward sweep—is far from established.

Hybrid Wings

Fixed-geometry wings having "composite" or "hybrid" planforms have been explored since the early days of swept-wing research as a means of providing an improved balance between slender wing supersonic benefits and subsonic requirements. However, it is only within the past two decades that aerodynamic technology has reached the point where extensive interest in hybrid wings utilizing slender wing benefits has been generated. Two of the primary applications are the vortex-lift-strake concept and the slender cranked-wing concept that were illustrated in Fig. 4. These concepts differ from most of the early concepts in that considerable emphasis is placed on combining the benefits of both attached flow and vortex flow.

Vortex-Lift Strakes

The latter part of the 1960's saw the beginning of the evolution of the vortex-lift-strake concept, in which the low structural weight and vortex-lift benefits of slender lifting surfaces are combined, in a synergistic manner, with the aerodynamic characteristics of a moderately swept wing designed for good subsonic and transonic performance.

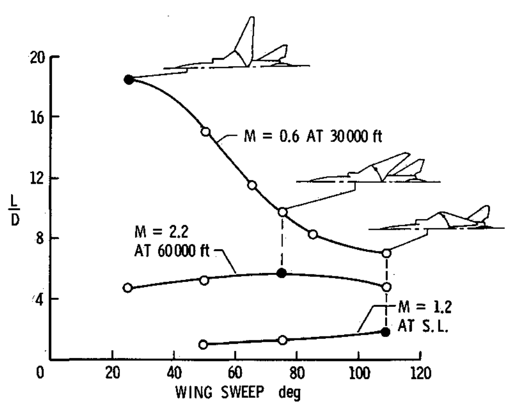

Fig. 8 Effect of sweep on aerodynamic efficiency, TAC 8 at 60,000 lb.

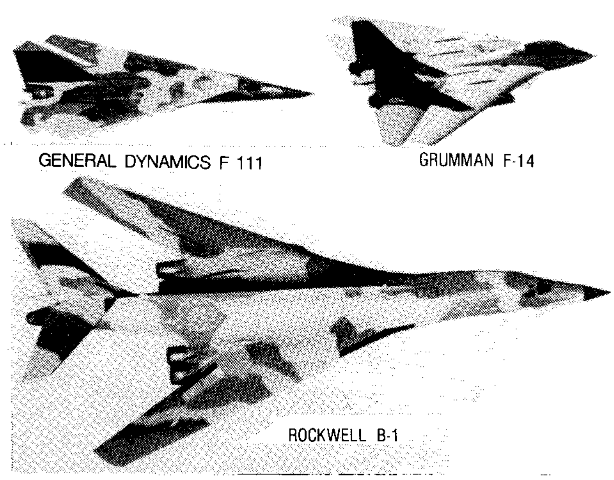

Fig. 9 Variable-sweep aircraft, slender wing mode.

Fuselage forebody strakes or chines had been used before, but primarily as a means of controlling the forebody effect on directional stability and reducing the aerodynamic center shift with Mach number The more recent application of slender surfaces is an integrated wing design concept providing multiple design points with considerable emphasis on high levels of transonic maneuver capability

The Langley Research Program

Langley research related to vortex lift began to accelerate in the mid-1960's Contributing to this interest was the extensive research in France and Great Britain in support of the Concorde program and its "controlled separation" concept, and the development at Langley of a concept that provided an improved understanding of vortex lift for arbitrary planforms This concept, referred to as the "leading edge suction analogy,"[28] offered the possibility of providing design and analysis aid and will be discussed in a subsequent section In addition to this growing vortex lift technology development, two events contributed to the initiation of a Langley vortex-lift-strake research program.

During the latter part of the 1960's, as Air Force interest in a new lightweight highly maneuverable fighter was growing, Langley researchers expanded their aerodynamic research in several related areas. One such research program by L W McKinney and associates[29 30] consisted of a detailed experimental and theoretical study of the maneuvering performance of both aft tail and close coupled canard configurations at high subsonic speeds Of particular interest was the favorable vortex induced mutual interference effects associated with close coupled canard configurations To provide additional data regarding the interference effects, a double-balance system was developed in which one balance measured the forces on the canard and forebody while the other measured those on the complete model (see Fig. 10)

As a result of this study and basic research related to the vortex lift of slender wings, it began to appear to the Langley researchers that the favorable effect of the canard trailing vortex, which resulted from the energizing effect its sidewash produced on the wing upper surface boundary layer near stall, might be extended to higher angles of attack by the highly stable leading-edge vortex flow of a slender lifting surface [29]

During the same time period, the Northrop Company noted a favorable impact on the maximum lift of the F 5A due to a small flap actuator fairing that extended the wing root leading edge This spurred interest in the influence of inboard vortex flow and led to the development of the YF-17 prototype aircraft in which a large highly swept leading-edge extension provided the nonlinear vortex-lift characteristics of slender wings and stabilized the flow over the moderately swept main wing in the high angle-of-attack range As part of the design work, a cambered leading edge was developed for the strake to suppress the vortex at low angles of attack and recover some effective leading-edge thrust in the vortex flow mode To describe the overall concept, they coined the term "hybrid wing "[31]

As a result of the Langley and Northrop vortex interaction studies, plans were formulated by mid 1971 for an expansion of the Langley program to investigate the hybrid wing approach with the slender lifting surfaces which became known at Langley as "vortex-lift maneuver strakes " The initial phase of the problem, reported by E J Ray and associates,[32] utilized a general research model having a moderately swept wing The tests, performed at subsonic speeds during the early fall of 1971, utilized the double balance technique to isolate the strake and wing loads These were the first tests to clearly illustrate the magnitude of the favorable effect that the strake vortex flow induces on the main wing panel flow at maneuvering conditions as illustrated in Fig 10 The total lift illustrates the nonlinear character of the lift produced by the strakes, which produces high levels of maneuver lift with essentially no increase in high speed low-altitude gust response The division of the lift produced by the addition of the strake, illustrates, in particular, the large lift increment produced on the main wing as the highly stable vortex from the strake reorganizes the flow and delays the stall on the outer panel Wing buffet measurements indicated that, while buffet onset occurred earlier, the intensity buildup was very slight, and large reductions in intensity were demonstrated in the maneuver lift range [32]

This study also demonstrated the large drag reductions in the high-lift range resulting from the strakes Recognizing that the degree of flow control on the main wing contributed by the strakes would be a function of the wing camber design, tests also were made with segmented leading edge flaps deflected to simulate a high lift design condition As was expected, the tests indicated that "as the wing design is

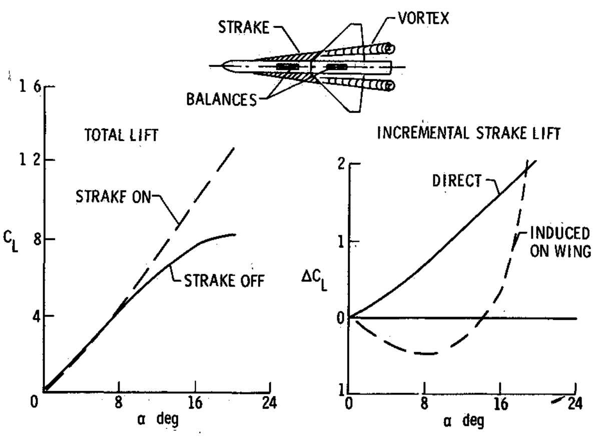

Fig 10 Effect of vortex strakes on lift; $M = 0\ 8$.

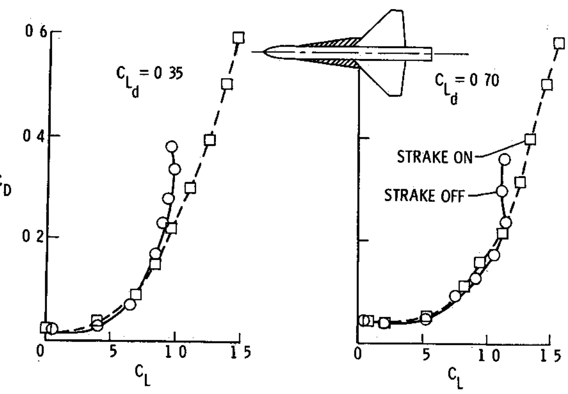

Fig 11 Effect of vortex strakes on drag; $M = 0\ 7$

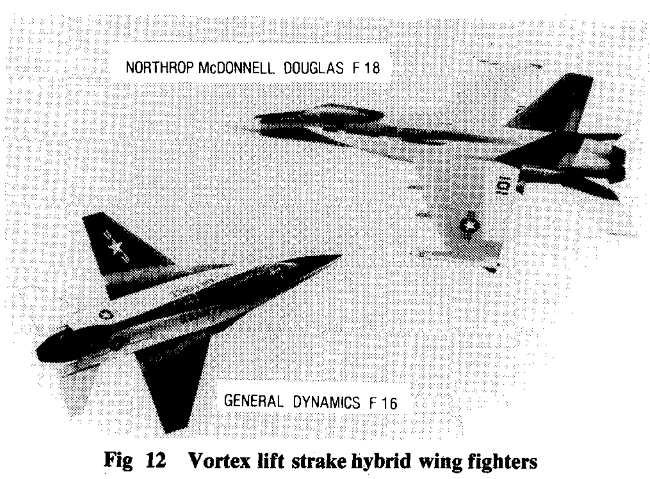

Fig 12 Vortex lift strake hybrid wing fighters

improved to delay separation on the main wing panel, the beneficial effects of the strake are delayed to increasingly higher angles of attack "[32]

Henderson and Huffman[33] extended the program to include wings warped for design lift coefficients of 0.35 and 0 70. Selected results are presented in Fig 11 and illustrate large benefits from the strake beyond the strake off wing stall region In the lower lift range, the strakes cause some increase in drag due to friction and the loss of leading edge thrust over that portion of the wing This problem subsequently was relieved by careful selection of the leading-edge camber of the strake

From these studies, it appeared that vortex lift strakes combined with variable wing camber in the form of programmed leading-edge flaps could provide a low structural weight approach for the high maneuverability levels desired by the Air Force

The Lightweight Fighters

In the fall of 1971, representatives of General Dynamics visited Langley to discuss a problem related to their lightweight fighter design study [34] The design incorporated a lifting fuselage in the form of a wide, flattened, and expanding fuselage forebody that blended into the wing The uncontrolled separation from the fuselage forebody was creating stability and performance problems at maneuvering conditions Based on their experimental and theoretical studies of slender sharp edged wings, where the separation is "controlled" by the fixed separation line, the Langley researchers suggested that the edge of the wide "lifting" forebody be sharpened In addition to controlling the forebody separation, this would increase the strength and stability of the vortex shed from the forebody, thereby increasing the vortex lift as well as stabilizing the high angle of attack flowfield over the aircraft.

General Dynamics then carried out an extensive wind tunnel program The lifting forebody was widened further to maximize the vortex lift benefit and a "blended" forebody strake evolved The detailed "fine tuning" by General Dynamics, aided by the concurrent Langley research, resulted in the now well-known vortex-lift strake of the highly successful Air Force F 16 lightweight fighter The F 16, shown in flight in Fig 12, utilizes a programmed leading-edge flap system to optimize the blend of the moderate sweep main wing aerodynamics with the "slender-wing" vortex flow benefits produced by the strakes to achieve an excellent balance of turning, cruise, and acceleration performance The strong vortex flow from the strake is clearly evident in the photograph

The Navy's newest fighter, the Northrop-McDonnell Douglas F-18 air combat fighter, is also illustrated in Fig 12. This aircraft evolved from the Northrop YF-17 aircraft which was based on Northrop's early work on the vortex strake "hybrid wing" concept

Slender Cranked Wings

By the mid 1970's, considerable interest in a supersonic cruise fighter aircraft had developed within the Air Force Referred to as a "supercruiser," it placed major emphasis on efficient supersonic cruise performance while maintaining respectable subsonic performance and maneuverability The strong emphasis on supersonic cruise tends to dictate a wing at the opposite end of the hybrid-wing scale relative to highly maneuverable transonic fighters In this case, it is the main wing panel that is made slender to improve supersonic cruise performance Again, both attached and vortex flows are combined

Langley Research Program

Langley researchers had a strong interest in the supercruiser concept as a result of the extensive supersonic aerodynamic design integration technology developed during the Langley supersonic transport program [35] Therefore, Langley embarked on a broad research program to investigate the degree to which this technology could be applied to supercruiser fighter aircraft A supersonic cruise integrated fighter (SCIF) design study was initiated in cooperation with the Air Force and various industry groups From the study, six designs evolved providing a matrix of performance capabilities, ranging from a $M=1\ 4$ design with emphasis on maneuverability, to a $M=2\ 6$ design with emphasis on cruise performance

Following supersonic tests,[36] two of the designs, designated SCIF 4 and SCIF 5, were selected for tests over the complete speed range to provide data for aircraft performance studies The two configurations are shown in the top portion of Fig 13 SCIF 4 is a $M=1\ 8$ design representative of an air-superiority fighter, while SCIF 5 is a more slender design with primary emphasis on a sustained supersonic cruise mission at $M=2\ 6$ Both are tailless configurations featuring hybrid wings of the slender cranked arrow type in which the highly swept inboard panels comprise the major portion of the wing in order to meet the supersonic cruise requirements At high angles of attack large levels of vortex lift are developed for the various high lift requirements. The smaller outer panels are cranked to provide reduced sweep and increased span for subsonic and transonic aerodynamic efficiency and improved handling qualities at high angles of attack

The SCIF configurations provided valuable information and details of the designs and aerodynamic characteristics are described by Shrout[37] and Morris.[38] The high levels of super sonic performance achieved will be described subsequently

Following the SCIF program, Langley extended its supercruiser program to include nonproprietary cooperative programs with the aircraft industry Slender cranked-wing configurations studied during the programs with General Dynamics and McDonnell are shown in the bottom portion of Fig 13. Initial studies[39] of the McDonnell configurations in the uncambered wing mode have been carried out at supersonic speeds and at low speeds Inasmuch as the cooperative program with General Dynamics eventually led to the F 16XL slender wing derivative prototype, that program is described in more detail

The NASA/General Dynamics Program

In May of 1977, an agreement was reached regarding General Dynamics' proposal for a cooperative research study applying a slender, cranked arrow wing to the F 16 to provide greater supersonic performance while attempting to maintain comparable transonic cruise and maneuver performance The selected wing planform, shown in Fig 13, had an area twice that of the F 16 and was of the cranked arrow type With the planform selected, a series of wing warps that would satisfy various supersonic aerodynamic loadings and F-16 fuselage constraints were designed and tested supersonically The best of the supersonic designs was then tested to establish the

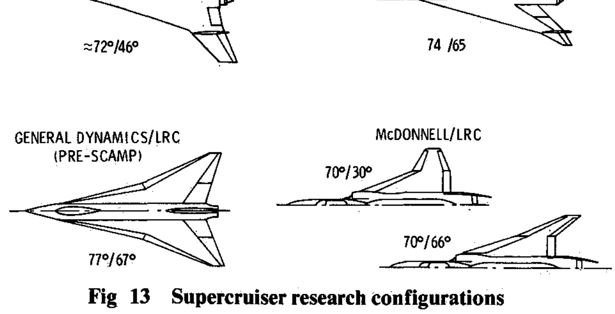

Fig 13 Supercruiser research configurations

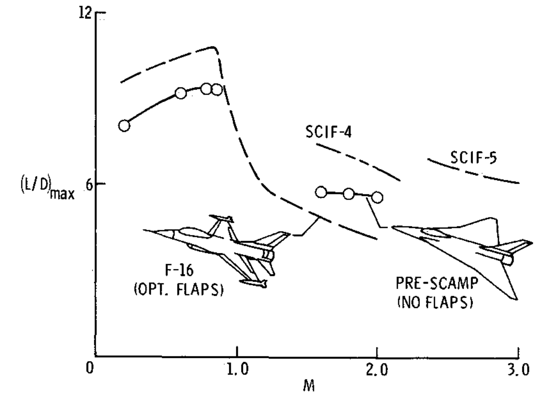

Fig. 14 Cruise aerodynamic efficiency.

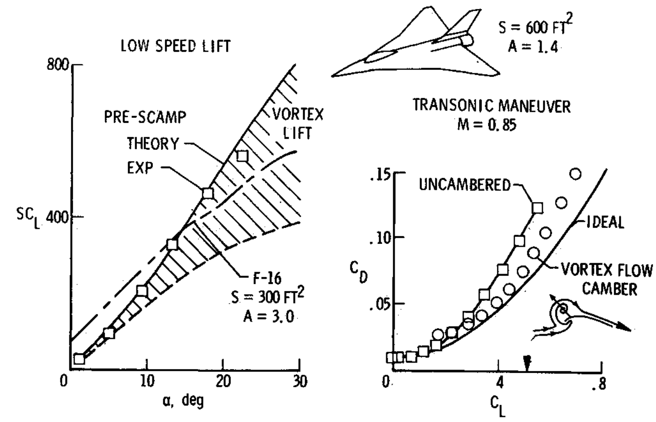

Fig. 15 Low-speed lift and transonic drag, PRE-SCAMP

subsonic and low transonic characteristics. This configuration is identified as PRE-SCAMP

A detailed description of the concept, wing design procedure, and the supersonic wind tunnel results are described by Miller and Schemensky.[40] An indication of the aerodynamic performance of the selected cruise configuration, in terms of maximum lift-to-drag ratio, is shown in Fig. 14. The supersonic results indicate that, while the PRE-SCAMP configuration does not reach the performance levels of the somewhat more idealized SCIF research configurations, it does provide considerable supersonic improvement relative to the F-16. It would appear that, with leading-edge devices, the slender cranked-arrow wing configuration should be within reach of the subsonic cruise performance of the F-16. Subsequent to this study, an improved method of accounting for the leading-edge thrust and vortex-lift effects for round-edge wings was developed by Carlson and Miller.[41]

In view of the fact that maintaining attached flow at high lifts is highly improbable for these slender wings, the "controlled separation" concept of vortex lift was utilized for the high-lift conditions. The left side of Fig. 15 illustrates the capability of the two configurations in terms of wing area times lift coefficient as a function of angle of attack. The results for the PRE-SCAMP illustrate the benefit of the increased wing area allowed by the low structural weight of slender wings, and the high level of vortex lift. The comparison with the basic F-16 with its flaps deflected indicates that the large slender wing of the PRE-SCAMP configuration provides comparable lift capability without using flaps. It will be noted that the vortex lift developed is well predicted by the suction analogy.[28]

A serious lift-dependent drag problem of slender wings, in addition to that associated with the low aspect ratio, is the loss of leading-edge thrust resulting from leading-edge separation. Therefore, another phase of the cooperative program was that of providing the slender wing supercruise concept with transonic-maneuver performance comparable to the current lightweight fighters. The study concentrated on the optimization of vortex flow To provide improved sustained maneuver capability, the application of controlled vortex-flow technology, under study at Langley, was utilized. Basically this consists of designing the leading-edge camber in the presence of the leading-edge vortex flow to optimize the effective leading-edge thrust produced by the vortex-induced lift on the forward-facing surface in the leading-edge region. Lamar had recently extended theoretical studies to cover slender wings in nonconical flow and had developed a pilot approach to a computerized optimization technique.[42] This general approach, modified to include structural constraints, was applied during the cooperative study. Since the study was directed toward the transonic maneuver case, a lift coefficient of 0.50 at a Mach number of 0.90 was selected as the design

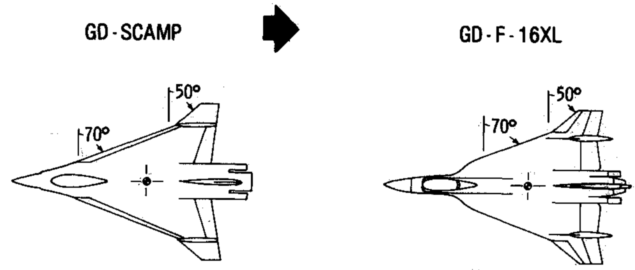

Fig. 16 Final stage of F-16XL evolution.

condition. Following the design study, wind tunnel tests were performed and a review of the complete study was reported by Lamar et al.[43] A brief summary of the results in the form of drag polars is presented on the right of Fig. 15 at $M = 0.85$, the highest Mach number available. Briefly, the results indicated that the vortex-flow design provided a sizable reduction in drag at the transonic maneuver point, but that a rather extreme amount of wing warp was required. A simple "vortex-flap" approximation to the desired warp provided encouraging results[43] and led to a research program described in a subsequent section.

F-16XL Evolution

The encouraging results led General Dynamics to embark on a company funded development of a wing for a "derivative" version of the F-16 with supercruiser-type characteristics. Although the cranked-arrow wing planform described previously was highly effective in increasing the supersonic performance and providing subsonic vortex lift, there were some concerns in the areas of weight and balance, subsonic performance, and low-speed flying qualities. This led General Dynamics designers to shift the wing design somewhat toward the subsonic requirements and to establish an in-house SCAMP study. The initial wing planform is shown on the left of Fig. 16 and, in comparison to PRE-SCAMP (Fig. 13), incorporates a larger span and reduced wing sweep angles, resulting in a cranked-arrow planform somewhat similar to the Langley SCIF-4 wing.

Early in the SCAMP study, General Dynamics made extensive low-speed wind tunnel tests to establish a means of providing adequate high-angle-of-attack stability and control. Langley researchers provided consultation and aided in the analysis. As a result, the configuration was modified as shown on the right of Fig. 16. To avoid the arrow wing pitch-up and lateral instability, the wing was biased toward the double-delta type by filling in the trailing-edge notch. Boundary-layer flow fences were added at the wing-break location, and a portion of the wing apex was removed. Some of the Langley studies related to the stability characteristics have been summarized by Johnson et al[44] This final configuration was tested in several Langley tunnels and became the slender hybrid-wing, F 16XL derivative aircraft shown in Fig 17 While benefiting overall from the vortex flow, the current version does not include the "vortex flap" and, therefore, experiences the drag increase at high angles of attack associated with the loss of leading edge suction.

This slender hybrid-wing provides the F-16 "derivative" aircraft with an excellent combination of reduced supersonic wave drag, controlled separation in the form of vortex lift, and low structural weight, while maintaining the wing span required for reasonable subsonic cruise performance Flight tests, which began in mid-1982, have confirmed the wind tunnel tests, and the aircraft is being considered by the Air Force as a possible advanced version of the F-16

Vortex-Flow Theory Development

The application of slender wings to provide efficient supersonic cruise and low-altitude high-speed penetration capability, and the trends toward maneuvers involving very high angles of attack, have been accompanied by some marked departures in wing design philosophy as illustrated by the above case histories The variable-sweep concept, which provides a near-optimum combination of slender wing high-speed benefits and classical subsonic type wing benefits, is based primarily on attached flow for which theoretical methods are in a relatively high state of development However, such is not the case for the fixed planform wings Here, the use of "controlled separation" to avoid stall progression problems, and to provide vortex lift, low speed performance, and transonic maneuver capability, has provided the designer of slender winged high-speed aircraft with an additional design philosophy to add to the time honored attached-flow approach Also, whether by design or not, many of the critical aerodynamic and structural design conditions encountered by slender wings involve leading edge vortex flows.

However, because of the relatively recent interest and the difficulty of the theoretical modeling, the designer has not been provided with theoretical methods comparable to those for attached flow The purpose of this section is to review some Langley contributions to vortex-flow theory develop ment related to eventual computer aided design methods

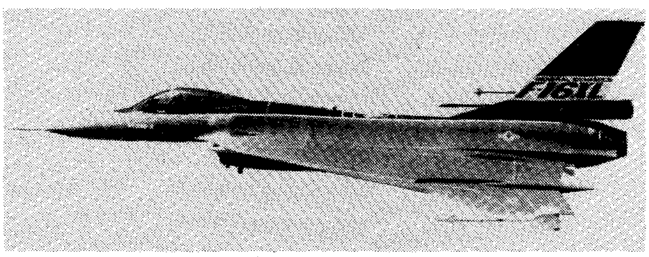

Fig 17 General Dynamics F 16XL

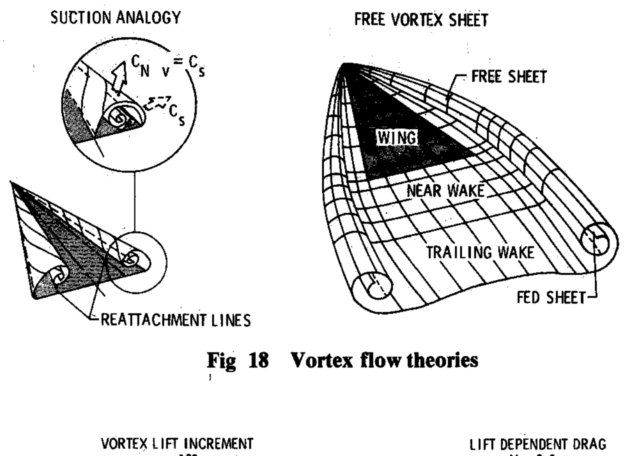

Fig 18 Vortex flow theories

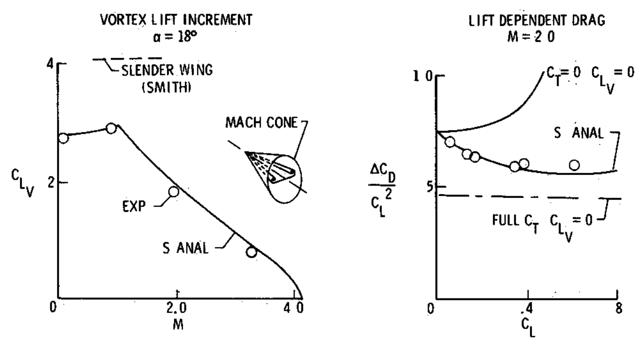

Fig 19 Prediction of vortex-lift characteristics, 76 deg delta wing

Background

The first theoretical approach to the vortex flow of slender delta wings was that formulated in France by Legendre[45] in 1953 Using a slender wing conical flow approximation, Legendre simplified the nonlinear system of equations resulting from the fact that neither the strength or shape of the free-vortex sheet is known His approach served as a basic model for many that followed.

The first theoretical method developed at Langley was the conical-flow model formulated by Brown and Michael[46] in 1954 which provided improvements over the Legendre model By the mid 1960's, many conical flow theories had been developed with the most notable being that of Smith[47] in Great Britain These theories provided insight into the vortex flow phenomena and contributed to early design concepts However, their applicability to wings of practical interest was limited by their inability to model three-dimensional effects such as, for example, trailing edge effects and the proximity of the Mach cone

Langley interest in vortex-flow theory was renewed in the mid-1960's with emphasis on completely three dimensional solutions The two primary approaches being utilized at Langley for slender wing design and analysis studies are illustrated in Fig 18. The suction analogy method relates the vortex induced normal force to the attached flow leading edge suction, thereby allowing overall forces and certain moment characteristics of arbitrary planforms to be calculated by linearized theory When detailed pressure distributions and flowfields are required, the free-vortex sheet theory is used

To provide alternate approaches, Langley has supported the development of some free vortex filament approaches in the university community, but these will not be described here

The suction analogy and free vortex sheet methods will be reviewed briefly in the following sections For a more complete description, the reader is referred to two review papers[48,49] and their cited references.

Leading Edge Suction Analogy

In 1966, the author conceived an analogy[28] that equated the attached-flow leading edge suction force to the normal force produced by the separation induced flow Although based partially on intuitive reasoning, the analogy allows accurate calculations of overall forces for arbitrary planforms at both subsonic and supersonic speeds[50] Also, it allows linearized flow theory to be used for this nonlinear flow phenomenon, thereby greatly reducing theoretical complexity as well as numerical run time and cost Its ability to overcome the limitations of slender wing conical flow theories led to an extensive program to extend its applications to the prediction of aerodynamic performance characteristics and stability derivatives for arbitrary wings

Performance Characteristics

The ability of the suction analogy to predict the subsonic lift and drag over a wide angle of attack range is well documented in the references, and an example of the subsonic lift predictions was given in Fig 15 An extensive program has been directed toward more generalized application with the work of Lamar and Luckring, reviewed in their summary paper,[48] representing a major portion While any potential flow theory that predicts leading edge suction accurately can be used to apply the analogy, a vortex lattice method of Lamar and Gloss[51] is generally used at Langley for the subsonic case

The ability of the analogy to predict the effect of supersonic flow on the lift and drag of slender wings is shown in Fig 19, taken primarily from an early study [50] On the left, the ability to account for the effects of the Mach cone on the vortex-induced lift C_{L_V} is shown for a slender delta wing at an angle of attack of 20 deg Also shown is the prediction by the slender wing conical flow theory of Smith [47] The ex perimental values were obtained by subtracting attached flow theory values from the total measured lift The results illustrate the ability of the suction analogy to predict the reduction in vortex lift encountered at supersonic speeds as the Mach cone approaches the leading edge The latter is associated with the forward movement of the stagnation line which reduces the vortex strength until the sonic leading edge case is reached and the leading-edge separation vortex vanishes The slender wing conical-flow solution[47] illustrates the magnitude of the discrepancies associated with the conical flow and small angle assumptions Since the vortex flow is primarily a high angle of-attack phenomenon, it is important that the classical small angle assumptions not be made.

The impact of the vortex flow on the lift-dependent drag parameter, C_D/C_L^2, as a function of C_L, is illustrated on the right of Fig 19 for a Mach number of 2.0 While the levels of drag are dependent on Mach number, the trends and basic phenomena shown are, in general, representative of most subsonic leading edge cases [50] The suction analogy and ex perimental results are in good agreement, and the drag in crease associated with the loss of leading-edge thrust due to leading edge separation diminishes rather rapidly with increasing lift coefficient This phenomenon is, of course, a result of the increasing flow entrainment induced by the vortex which allows the lift to be generated by accelerating a larger mass of air through a smaller deflection angle and, as indicated in Ref 50, has implications with regard to camber requirements at the higher lifts Interest in these effects has expanded recently as indicated by application of the analogy to other supersonic theories such as, for example, that of Carlson and Mack [52]

Most applications of the analogy have been for sharp leading edges However, during the early Langley studies it was noted that for round leading-edge wings, where separation is no longer fixed by a sharp leading edge, the sum of the vortex-induced normal force and the remaining portion of the leading edge suction was equal to the attached flow leading edge suction This apparent "conservation of suction" phenomenon was further explored by Henderson[53] indicating this phenomenon to be consistent for Reynolds number effects as well as leading edge radius effects More recently, these observations have been developed by Carlson and Mack[54] into a vortex-flow prediction method for both subsonic and supersonic flow

Stability Characteristics

Important in the design of slender wing aircraft is an un derstanding of the influence of vortex flow on the various stability characteristics Although the suction analogy does not predict the complete surface load distribution, it has provided the basis for some useful stability related prediction concepts

Figure 20 illustrates two applications of the analogy related to slender wing stability characteristics Regarding the overall longitudinal load distribution related to the longitudinal stability and pitch damping, Snyder and Lamar[55] have shown that the analogy provides an accurate prediction Their results illustrate the strong trailing edge effects which limit the usefulness of conical-flow theories

Turning to roll damping, Boyden[56] applied the suction analogy and developed a theoretical method of predicting the strong vortex-induced damping effect on the steady state roll damping Lan[57] extended the theory to include the oscillatory case As shown on the right of Fig 20, good agreement with experimental results is obtained A trend toward negative damping at high angles of attack for the lower reduced-frequency parameter is seen—a characteristic that can in fluence the "wing rock" phenomenon

Free Vortex Sheet Theory

To provide a method that models the complete flowfield and establishes surface pressure details, Langley contracted with the Boeing Company in 1973 to develop a high-order panel method to model the leading edge vortex flow A schematic of the resulting theoretical model, known as the free vortex sheet (FVS) method, is shown on the right of Fig 18 The vortex sheets are modeled with biquadratically varying doublet panels representing: the free sheet shed from the separation line, the fed sheet which is a simplified model of the vortex core region, a higher order near wake, and a frozen trailing wake Neither the shape of these three dimensional sheets nor the distribution of vorticity strength is known a priori, resulting in a nonlinear problem requiring iteration schemes The initial development work and some early applications were described by Gloss and Johnson,[58] and a current form of the computer program has been documented by Johnson et al [59]

The purpose of this development is to provide technology that will eventually lead to vortex flow design capabilities comparable to those available for attached flows [60] In ad dition to working closely with Boeing during the develop ment, Langley researchers have made comprehensive validation and application studies, some of which have been reviewed by Luckring et al [61] Reference 61 describes the investigation of convergence techniques for both the wing flow and the near-wake flow as a means of reducing computational cost, and presents several examples of practical applications to nonsymmetrical conditions, side edge separation, compressibility effects, vortex flaps, and blast induced loads encountered during low-altitude penetration missions

Pressure Distributions

An illustration of the strong nonconical flow effects en countered even on very slender wings is shown in Fig 21, taken from Ref 61 Here the upper surface spanwise pressure distributions obtained from the free-vortex sheet theory for

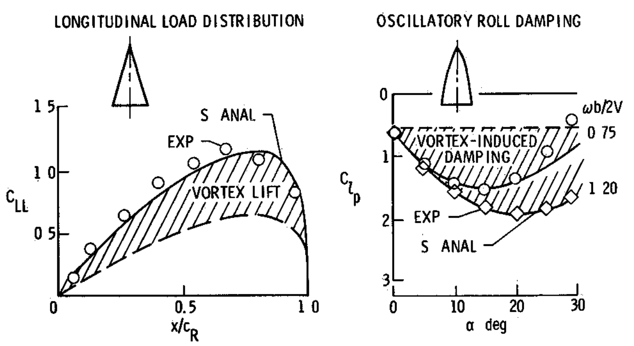

Fig 20 **Prediction of stability related parameters**

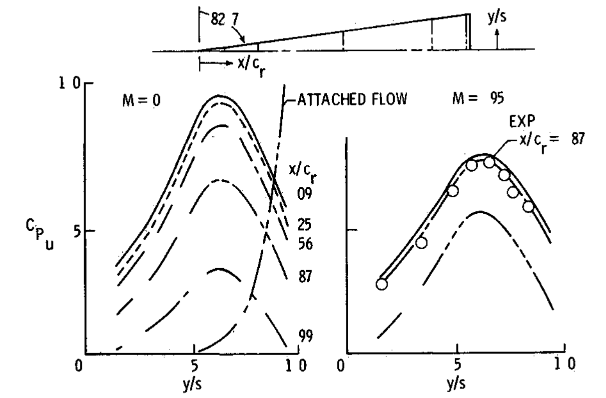

Fig 21 Theoretical spanwise pressures, FVS theory; $\alpha = 21$ deg

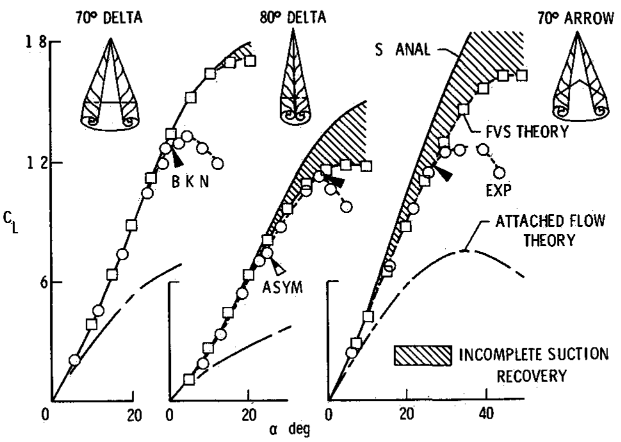

Fig 22 Effect of vortex size on C_L

an 82 7 deg delta wing at an angle of attack of 21 deg are presented for various longitudinal stations The in compressible case illustrates the strong effect of the trailing edge and indicates that the pressure distributions are nowhere conical An indication of the extreme difference between attached and vortex flow pressure is shown for the 0 87 station As the Mach number is increased to 0 95, the trailing-edge effect is essentially limited to the aft 10% of the wing, and, of course, the flow would be expected to be fully conical at sonic speed Also shown is the experimentally determined pressure distribution for $x/c_r = 0$ 87 Good agreement is obtained and additional experimental confirmation is presented in Ref 61 Some differences, of course, have been observed near the leading edge since the small secondary vortex is not modeled

Lift Characteristics

The degree to which the fully available vortex lift is realized on slender wings is, of course, highly dependent on the vortex breakdown characteristics However, an additional limitation that can be important is related to the vortex size Figure 22 compares solutions obtained from the free vortex sheet theory and the suction analogy Also shown are experimental results for sharp edge wings [62] The wings were selected to illustrate the effect of vortex size as influenced by both leading- and trailing edge sweep angles The lift calculated by the suction analogy is believed to provide the "upper bound" of lift for conditions where no losses associated with vortex size or vortex breakdown are encountered (Breakdown is indicated by the arrows labeled B K'N)

For the 70 deg delta wing, the suction analogy and the free vortex sheet theory are in excellent agreement up to about an angle of attack of 40 deg, and both agree with experiment until vortex breakdown is encountered However, for the 80 deg delta wing, the free vortex sheet solutions begin to show lift losses relative to the suction analogy (indicated by the shaded area) beginning at about 15 deg It is believed that the relatively larger vortices on this very slender wing begin to "crowd" each other, thereby hindering flow reattachment and full suction recovery

The effect of trailing edge sweep can be seen by comparing the results of the 70 deg delta and 70 deg arrow wings For the arrow wing, the free-vortex sheet solutions begin to depart from the suction analogy at an angle of attack of about 10 deg In this case, instead of vortex "crowding," the loss is believed to result from the fact that as the vortex size increases the arrow wing does not provide sufficient area near the tip to allow full reattachment of the flow Therefore, a loss of suction recovery occurs This effect, of course, contributes to the pitch-up problem of arrow wings

The high angle of-attack decrement between the suction analogy and experiment often has been attributed in full to vortex breakdown effects. However, from the above ap plications of the free vortex sheet theory, it appears clear that much of this lift loss, in fact, is associated with vortex size effect as proposed previously in Ref 50 With the free vortex sheet code now in a production mode, its application to numerical experiments should be accelerated

Emerging Technology

The insight provided by the free-vortex sheet solutions should also be useful in interpreting the subsonic results that are beginning to emerge from Euler and Navier-Stokes solutions [63 65] For example, much of the lift loss, attributed to the possibility of vortex breakdown being modeled by these solutions may, in fact, be associated with the vortex size effect just described From a broader perspective, the development and application of these methods which provide more complete fluid mechanical representations than, say, the free vortex sheet is to be encouraged Currently, it would appear most fruitful to concentrate on the sharp-edge case with separation fixed at the edge However, as high Reynolds number turbulence modeling capability emerges, the Navier Stokes solutions should be applied to Reynolds number critical effects such as, for example, the split between the leading edge thrust and the vortex lift mentioned in a previous section

Some Design Technology

In this final section, some examples of vortex flow design technology that may contribute to future applications of slender wing benefits will be reviewed briefly

Vortex Lift Strakes

With the maneuver performance benefits demonstrated by the wind tunnel studies having been confirmed by flight tests of the F 16 and F-17, the Langley Research Center extended its vortex lift strake research in several areas to provide additional design technology for possible future applications Two of the primary areas were the effect of wing planform on strake wing interactions and design criteria related to the delay of vortex breakdown

A brief summary of the theoretical and experimental study by Luckring[66] regarding the effect of wing planform on strake wing interactions is given in Fig 23. Using five wings having leading edge sweep angles from 30 to 60 deg and three sizes of strakes, tests were performed, at low speeds, using the double balance technique Luckring also developed a theoretical model of the high-angle of attack vortex in teractions[66] by extending suction analogy concepts related to carryover loads [67]

This extensive parametric study provides considerable design guidance Only a small portion can be reviewed here, with examples being selected from the results obtained with

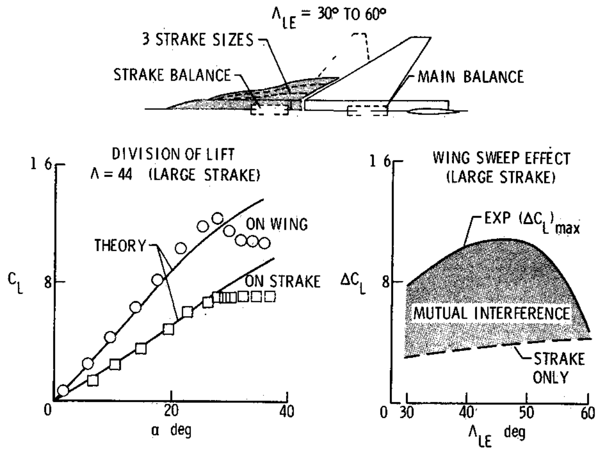

Fig. 23 Strake wing parametric study

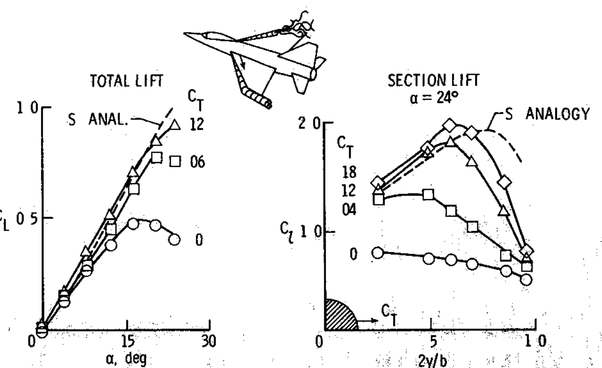

Fig 24 Effect of spanwise blowing; $M = 0.3$, $\Lambda_{le} = 44$ deg.

the large strake. On the left of Fig. 23, the division of load between the strake forebody and wing afterbody com binations are shown as a function of angle of attack These results indicate excellent agreement between theory and experiment up to the region of vortex breakdown Illustrated on the right is the effect of the sweep angle of the main wing panel on the maximum increment in lift coefficient, $(\Delta C_L)_{max}$, associated with the addition of the large strake The strake increment is seen to increase, reaching a maximum level in the vicinity of a main wing sweep angle of 45 deg, followed by a rapid decrease between 50 and 60 deg This decrease is not surprising since the more highly swept wings develop a relatively stable vortex flow without the aid of the strake To place these maximum strake increments in perspective, the strake increment, with the wing off, at the angle of attack for which $(\Delta C_L)_{max}$ occurred, is shown by the dashed line The shaded area between the curves represents the mutual in terference between the strake and wing and illustrates the large, synergistic benefit of the strake for wing sweep angles up to about 50 deg It also graphically illustrates the fact that the synergistic effect diminishes rapidly as the natural stable vortex flow develops on the wing For more details of strake wing interactions the reader is referred to Ref 66

Regarding the vortex breakdown characteristics of strake-wing combinations, a parametric theoretical and experimental study has been carried out by Lamar and Frink [68] Briefly, they have shown that, by shaping the strake planform to produce a prescribed growth of the vortex lift increment in the longitudinal direction, a more stable vortex can be produced

Jet-Augmented Vortex Concepts

Another general approach for providing vortex flow benefits on the moderately swept, higher aspect ratio wings of interest for transonic maneuvering aircraft is the application of various jet powered vortex augmentation schemes which maintain a tighter vortex and delay breakdown by the ad dition of energy to the vortex system A review of the various concepts is presented in Ref 49 Only the spanwise blowing concept will be described here

Spanwise blowing appears to have been proposed first in the present context by Cornish of Lockheed [69] In this concept, the beneficial effects associated with large leading edge sweep angles are simulated on moderately swept wings by the action of a jet blowing over the upper surface of the wing in a direction approximately parallel to the leading edge The added energy (analogous to that associated with the increase in the local "effective" sweep angle) provides vortex stability and delays vortex breakdown to increasingly higher angles of attack as the jet thrust coefficient, C_T, is increased

A considerable amount of research has been carried out at Langley with the detailed pressure distribution studies by Campbell[70 71] providing the type of aerodynamic information required for the design and analysis of a practical system Some of this information, obtained on a wing having 44 deg of leading-edge sweep, is presented in Fig. 24 On the left-hand side is shown the overall lift effectiveness for a range of thrust coefficients. It will be noted that, for a value of C_T of 0 12, the total lift has been increased until it is in the range of that predicted by the suction analogy By comparison with the nonblowing case, it is seen that lift coefficient increments equivalent to five times the thrust coefficient are achieved in the high-angle-of-attack range.

The effect of thrust coefficient on the spanwise penetration of the jet-induced vortex stability can be seen on the right-hand portion of Fig. 24 where the spanwise variation of the section lift coefficient is presented for an angle of attack of 24 deg Also shown is the spanwise variation of the section lift coefficent as predicted by the suction analogy For reference, the zero blowing case is shown illustrating the large loss of lift across the entire span due to vortex breakdown and leading-edge stall As blowing is applied, the inboard stations quickly reach the general level predicted by the suction analogy. However, even for the largest value of C_T the jet penetration is such that full vortex lift is limited to the inboard 60% of the wing span This suggests the use of an additional jet nozzle on the outboard wing panel

Additional research has also been carried out at Langley The studies by Erickson and Campbell[72] deal with both performance and stability Research by Anglin and Satran[73] relate to beneficial effects on roll damping and wing rock A joint program between Langley and the Dryden Flight Research Facility, directed toward a flight demonstration of the application of inboard and outboard spanwise blowing to fighter maneuverability, is currently underway

Vortex Flaps

While vortex lift alleviates the lifting deficiency of slender wings, the high drag associated with the loss of leading-edge suction has been a continuing problem with slender wing aircraft. As mentioned earlier, studies by Lamar et al.[42 43] led to an increased understanding of vortex-flow design optimization of the three dimensional wing camber distributions required to improve the efficiency of vortex maneuver lift. These studies stimulated an extensive research program directed toward the development of practical variable geometry devices for controlled three-dimensional separation and vortex management on slender wings A notable example of such a device is the "vortex flap" which provides a practical approach for approximating the vortex flow camber distribution required to provide high levels of sustained maneuver performance for slender wings

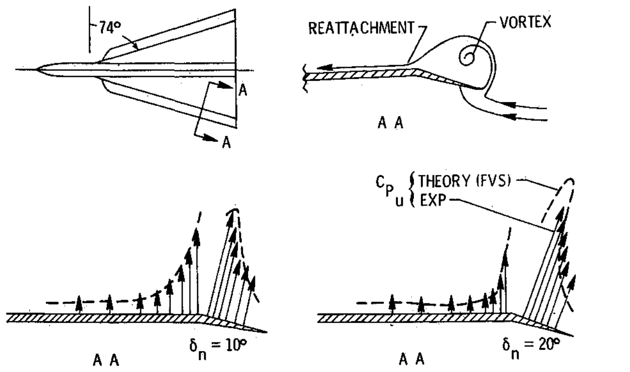

Fig 25 Vortex-flap concept; $M = 0\ 3$, $\alpha = 14$ deg

In the period following the wing camber investigation, Rao, under a Langley contract, initiated an extensive experimental investigation of a wide variety of vortex-flap and other vortex-management concepts Rao's research has provided an extensive data base useful for preliminary design concepts. The reader is referred to his summary papers[74 75] and their cited references A study of a vortex-flap application using a specific slender wing aircraft design was carried out by Smith et al.[76] as part of the cooperative program with General Dynamics related to the SCAMP investigation

Of the various vortex management concepts, the vortex flap is currently receiving considerable design attention The basic type under investigation is a relatively simple hinged leading-edge flap having a sharp leading edge and deflected in the nose-down direction. While leading edge flaps had been utilized in the past as a means of suppressing or modulating the leading-edge vortex flow, the vortex flap described here is unique in that it utilizes the vortex flow to provide an optimum combination of leading-edge thrust and flow reattachment on the wing at the high-lift condition required for sustained high load-factor maneuvering This is illustrated in Fig 25. Since at the maneuvering lift coefficients some type of separation is almost inevitable, a controlled leading edge separation is selected with the vortex lift concentrated on the flap such that it provides a sizable forward, or thrust, component In addition, the flap is designed such that the vortex induced flow reattachment occurs at the hingeline thereby affording the possibility of attaining attached flow over the remainder of the wing The vortex induced contributions of partial thrust recovery and possible attached flow aft of the hingeline combine to offer an attractive and practical alternative to the very difficult attached flow design problems for high maneuver lift conditions

Controlled separation also reduces the sensitivity of performance to off-design conditions—a particular advantage for tactical aircraft. Also shown in Fig 25 are upper surface pressure measurements on a simple constant chord flap from one of Rao's studies and the corresponding free vortex sheet calculations made by Frink [77] The experimental and theoretical results are in reasonably good agreement and illustrate the vortex-flap concept; however, it will be noted that, for these cases of less than optimum flap angle, the reattachment line occurs aft of the flap hingeline Therefore, some effective thrust recovery is lost

Design methods which can place the reattachment line close to the flap hingeline along the entire flap span are required to provide optimum maneuver performance. An extensive design study is underway which uses simplified theoretical approaches for the preliminary design and applies the more detailed free vortex sheet theory to evaluate and improve the resulting designs Some of the early results of this study have been published by Frink [77]

Other studies, in addition to the previously mentioned joint study with General Dynamics, are the cooperative program with Boeing described by Schoonover and Ohlson[78] and a Northrop study summarized by Erickson [79]

Concluding Remarks

Aerodynamic research, following the general approaches pioneered by the Wright brothers, has continued to make important contributions to the development of advanced aircraft Regarding the application of slender wing benefits to modern high speed military aircraft, we have seen such research provide a selection of viable approaches in the form of both variable-sweep and fixed planform wings

Variable sweep research has led to a series of supersonic aircraft which have successfully combined slender wing benefits with those of the classical subsonic wing to provide a high degree of multi design point capability

For fixed planform slender wing aircraft requiring less multi design point capability we have seen a new wing design philosophy emerge in which separation-induced vortex flow is combined with the time honored attached flow to expand the performance capabilities To improve the design technology for this "controlled separation" concept, improved vortex flow theories are being developed; but the effort should be accelerated and expanded to provide computer aided design capability The usual drag penalty associated with vortex flow is being alleviated with devices such as the "vortex flap," and such research must continue in order to achieve full benefits of slender wings

Research has indicated strong effects of Reynolds numbers on the tradeoff between leading-edge suction and vortex lift; the new National Transonic Facility should provide valuable information in this regard.

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