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EFFECTS OF JETS, WAKES, AND VORTICES ON LIFTING SURFACES

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16. Abstract

This paper reviews a number of aspects of the effects of jets, wakes, and vortices on lifting surfaces for a variety of aerodynamic situations. The intent of the paper is to highlight representative work related to this subject without pretense to being a complete, exhaustive compilation of research activity. It shows that lifting-surface performance can be significantly affected by jets, wakes, and/or vortices.

Aircraft wings and control surfaces must operate in flow fields influenced by many factors including their mutual interaction. At moderate angles of attack, the wakes generated by lifting surface induce twist and camber distributions over the entire aircraft. At high angles of attack, leading-edge vortices and flow separation often occur which can create more severe wake effects. Several examples of current work are presented.

Throughout the angle-of-attack range, there are also propulsion flows. Their significance depends on the aircraft configuration and thrust level. STOL, V/STOL, and military combat aircraft must be designed to take advantage of these flows to satisfy their performance requirements. Current prediction methods and illustrative experimental data are presented.

During aircraft operations near terminals, the wakes of large jet aircraft pose a significant hazard to any smaller aircraft that follow. A summary of the large current effort in this area shows the status of this work and indicates hope for aerodynamic methods which reduce operating problems.

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SUMMARY

Aircraft wings and controls surfaces must operate in flow fields influenced by many factors including their mutual interaction. At moderate angles of attack, the wakes generated by lifting surfaces induce twist and camber distributions over the entire aircraft. At high angles of attack, leading-edge vortices and flow separation often occur which can create more severe wake effects. Several examples of current work are presented.

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SYMBOLS

AR	aspect ratio, b^2/S
b	wing span
c	wing chord
C_D	drag coefficient, Drag/(qS)
C_{D_o}	zero lift-drag coefficient
C_L	lift coefficient, Lift/(qS)
C_{L_D}	design lift coefficient
$(C_{l,TW})_{max}$	maximum rolling-moment coefficient induced on a trailing wing by vortex wake
C_m	pitching-moment coefficient, Pitching moment/(qSc)
C_N	normal-force coefficient, Normal force/(qS)
C_S	leading-edge suction-force coefficient, $K_{vle}\lvert\sin\alpha\rvert\sin\alpha$
C_μ	momentum coefficient, Thrust/(qS)
e	drag-due-to-lift efficiency parameter
h	height between wing and canard
K_p	potential-lift factor, $\frac{\partial(C_{N,p})}{\partial(\sin\alpha\ \cos\alpha)}$
K_{vle}	leading-edge-vortex factor, $\partial\left[\frac{\left(\frac{\text{leading-edge suction force from one side}}{qS}\right)}{\partial\ (\sin^2\alpha)}\right]$
M	Mach number

q	dynamic pressure
R	Reynolds number
S	wing area
V	velocity
V_e	effective velocity ratio, $\sqrt{\frac{\rho V^2}{\rho_j V_j^2}}$
α	angle of attack
δ	deflection
Λ	leading-edge sweep angle
ρ	density

Subscripts:

f	flap
j	jet
p	potential flow
t	tail
TRIM	trimmed
vle	leading-edge vortex
w	wing

1. INTRODUCTION

The interaction of jets, wakes, and vortices on lifting surfaces represents a broad spectrum of aerodynamic flow phenomena. In the present paper, jets will be defined as propulsive flows whose velocities are greater than free-stream velocity. While wakes will be defined as flows whose velocities are less than free-stream velocity. Vortical flows will include both separated edge and trailing vortices. The effects of each factor alone on lifting surfaces can be significant. In addition, their combined effects on lifting surfaces is an important aspect.

The first section discusses jet/lifting-surface interactions which can be significant in cruise and which are critical at low speeds for powered-lift, propeller slipstream, jet VTOL, and rotorcraft. These interactions occur throughout the angle-of-attack range where propulsion flows influence the performance of lifting surfaces. Their significance depends on the aircraft configuration and thrust level. STOL, V/STOL, and military combat aircraft must be designed to take advantage of these flows to satisfy their performance requirements. Current prediction methods and illustrative experimental data are presented.

The second section discusses wake/lifting-surface interactions for several aerodynamic situations. In aircraft design, both the direct and indirect effects of aerodynamics must be accounted for. One aspect of these designs is the mutual interaction of lifting wings and nearby control surfaces. Several examples of these factors are described. In addition, there are many instances of wakes caused by flow separation. The effects of airfoil flow separation are presented with an emphasis on multi-element high-lift airfoil applications.

The third section discusses two major areas of vortex/lifting-surface interaction. The first area deals with separated edge vortices such as those generated on leading-edge strakes, high sweep wings, wing tips, and the edge of partial-span flaps. The majority of these effects relate to supersonic aircraft or high performance combat aircraft. The second area deals with wake vortices. In one case, wake vortices may influence aircraft either for close formation flight, for mid-air refueling operations, for agricultural aircraft spray patterns, or for helicopter blade vortex interaction. In a second case, wake vortices from large transport aircraft are a hazard to following aircraft. This hazard is quite significant in the final approach to landing at an airport and persists for large distances behind the generating aircraft. One example of research to identify and locate wake vortices near airports is described.

In addition, an example of a possible technique for vortex alleviation applicable to contemporary civil transports is presented.

In the final section, the effects of combinations of jets, wakes, and/or vortices on lifting surfaces is considered. A few examples of these combined effects are described. In some examples, the combined effects are mutually beneficial; in other examples, the combined effects create a need for airplane design changes to avoid adverse effects.

Overall this paper surveys a broad area of current aerodynamic research. The interaction of jets, wakes, and vortices on lifting surfaces must be considered in a wide variety of circumstances. The purpose of the present paper is to highlight a representative sample of appropriate research activities.

2. JET/LIFTING-SURFACE INTERACTIONS

Jet/lifting-surface interactions (Fig. 1) can be significant in cruise and critical at low speeds for powered, propeller slipstream, jet VTOL, and rotorcraft. In this section of this paper, the cruise and low-speed effects will be examined. For the purpose of this paper, jets are propulsive flows whose velocities are greater than free-stream velocity.

2.1 Effect of jets in lifting surfaces in cruise

For many years, propulsive jets have only influenced base drag; however, this is not true for many of the configurations introduced in recent years. In particular, transports with upper-surface blowing (that is, YC-14), or to a lesser degree, externally blown flaps (that is, YC-15) can produce significant interaction between the jet exhaust and the wing in cruise. High subsonic speed experimental data are limited at the present time.

One of the earliest investigations on the influence of a propulsive jet close to a wing upper surface was conducted by Falk (Ref. 1) in the 1940's. Within the last several years, additional investigations have been conducted by Putnam (Ref. 2) and Shollenberger and Kotansky (Ref. 3). Putnam obtained data for an aspect ratio 3, swept (Λ = 50), tapered (λ = 0.3) wing over a Mach number range from 0.4 to 0.95. Shollenberger and Kotansky's tests were conducted to provide a data base for validation of analytical predirection schemes and to provide insight into fundamental behavior of wing and jet combinations. Their results include a variety of wing and jet parameters, including wing angle of attack, wing aspect ratio, jet position, jet angle, and jet/free-stream velocity ratios.

There are a number of military combat aircraft configurations (Ref. 4) with large propulsion-induced aerodynamic interaction. These experimental data are appropriate for both cruise and maneuvering flight conditions and include the effects of over-the-wing blowing, upper-surface blowing, and deflected or reversed thrust. These results show that with proper integration of the powerplant and the airframe, significant improvements in cruise performance of both fighter and transport aircraft are possible.

There have been several analyses of over-the-wing blowing configurations. One method by Putnam (Ref. 5) uses a vortex-lattice representation of the wing lifting surface and a line sink-source distribution to simulate the effects of the jet exhaust on the wing lift and drag. The predictions of the relatively simple procedure are very good for application at subsonic speeds ranging down to minimum flight speeds used by conventional aircraft. Another more complex theory by Lan (Refs. 6 and 7) accounts for the differences between the jet and free-stream Mach number. The results from Lan's theory provide good agreement with experiment down to minimum flight speeds for STOL aircraft. There are two jet-flap theories (Refs. 8 and 9) for two-dimensional wings in transonic flow. These methods include both jet-flap and shock-induced effects.

Propulsive efflux can also interact with longitudinal control surfaces. These influences should be considered during the design of an empennage which may experience either large downwash or dynamic pressure changes. In some situations, increased jet-induced velocities at the horizontal tail can reduce the area required or that changes in downwash angle can change the tail incidence required for trim.

2.2 Effect of jets in lifting surfaces at low speeds

The effects of jets on lifting surfaces at low speeds have received considerable attention for STOL, V/STOL, and rotor and military combat aircraft. These aircraft must be designed to take advantage of propulsive efflux or jets to satisfy their performance requirements. A detailed description of much of the technology and their application to STOL aircraft is presented in a compilation of papers (Ref. 10). In particular, the aerodynamics, loads, and flight dynamic sections of Reference 10 provide many illustrations of the effects of jets on lifting surfaces. These effects are demonstrated on many aircraft concepts: externally blown flaps, upper-surface blown flaps, augmentor wing, jet flaps, deflected-thrust plus double-slotted flaps, and others. Two of these concepts (Refs. 11 and 12) are currently in flight tests for the U.S. Air Force.

A typical example of the effects of thrust on powered lift are shown in Figure 2 for the externally blown flap (EBF) concept (Ref. 13). The EBF concept uses the engine exhaust flow to produce an incremental lift on the wing by a directed deflected-thrust vector and increased circulation lift by flow through the flap slots; it thereby enhances the lift-producing capabilities of the total lifting system. As shown in Figure 2, there is a large increase in lift coefficient as the momentum coefficient is increased from 0 to 3.74 for a configuration with a high flap deflection. The lift-drag polar shows that the large lift coefficients are obtained with a drag coefficient appropriate for descending flight. This configuration had the tail off. As shown by the pitching-moment coefficient curve, there is a large nose-down pitching moment which must be trimmed by the horizontal tail. Some of the trim problems can be difficult to overcome, one example will be given in the final section of the present paper.

Along with the EBF concept, the upper-surface blown (USB) flap concept has been the subject of many investigations in the last 5 years. For example (Ref. 14), one study examined a thick wall jet deflected by a convex surface showed that effective flow turning can be achieved, but that it is sensitive to the speeds of both the jet and the surrounding free stream. Further it was found that incompressible, inviscid flow theory can be useful for predicting wing pressure distributions and static turning angles at moderate Mach numbers.

Several studies (Refs. 13 and 15) have shown that propulsion-induced lift increases the need for wing leading-edge protection to prevent separated flow. It has been shown (Ref. 16) for an EBF configuration that flow angles as high as 67° can be induced at lift coefficients of 4 and 25.7° angle of attack. Proper leading-edge treatment is, therefore, critical to achievement of maximum lift. An example of an investigation (Ref. 15) for an USB flap configuration shows at high-lift coefficients that the presence of four large nacelles mounted above the wing and at inboard locations produces large upwash angles between the nacelles and near the fuselage. Several changes in the leading-edge configuration and nacelle shape were shown to be effective in providing maximum lift improvement.

Propeller slipstreams can also produce large effects on lifting surfaces. These effects have been well documented (Refs. 17 and 18) for deflected slipstream and tilt-wing aircraft in the past 10 years. At the present time, there is an increasing interest in turboprop propulsion for subsonic transports. It is expected that such aircraft will experience noticeable propulsion-induced effects especially at low speeds while taking off and landing. There have been a large number of theoretical analyses of propeller slipstreams. Particularly significant is the early work of Rethorst (Ref. 19). As new work on turboprop aircraft begins, it is expected that there will be additional analysis (Refs. 6 and 20) improvements.

High disk loading V/STOL aircraft experience propulsion-induced effects on lifting surfaces in the transition speed range between hovering and conventional flight. There have been a large number of experimental and analytic investigations conducted to evaluate these effects. A comprehensive workshop describing current V/STOL activity (Ref. 21) was conducted last year by the Naval Air Systems Command. A summary (Ref. 22) of the work shop describes the current status of much of this activity.

One example (Ref. 22) of the V/STOL propulsion/lifting-surface interaction is presented in Figure 3, and shows the sensitivity of the induced effects to jet locations near the wing trailing edge. The jets were located at three different positions: the baseline position corresponding to the original model and positions 15-percent local wing chord fore and aft of the baseline position. The adverse effect is reduced and changed to a beneficial effect as the jet exits are moved toward the wing trailing edge. Other examples of jet/lifting-surface interaction are plentiful for V/STOL aircraft and tend to be very configuration oriented. These examples include hover lift interference, thrust augmenting/ejector/wing interaction, location of the jet vertical and longitudinal position with respect to the wing and inlet induced effects.

Helicopter induced flow velocities can be large in the region of the fuselage, wing, empennage and rocket firing stations at hover and in low-speed flight. Accurate estimation of these induced velocities is needed to properly evaluate the low-speed performance of helicopters. The history of helicopter performance prediction methods and the influence of rotor wakes are traced by Landgrebe and Cheney (Ref. 23) from simple momentum techniques used in the early years of propellers and rotors to current state-of-the-art computer programs which simulate the complex vortex structures of the rotor and its wake. Early methods became inadequate as disk loadings increased and wake effects became increasingly important.

Currently Landgrebe and Egolf (Refs. 24 and 25) have developed a lifting-line rotor blade analysis with wake modeling options for undistorted and distorted, calculated and experimental wake geometries. In another program, Kocurek and Tangler (Ref. 26) have applied lifting-surface theory to the calculation of rotor hover performance and have used a prescribed near wake model based on schlieren flow visualization. Their qualitative comparison between lifting-line and lifting-surface methods indicates the tendency of the lifting line to develop larger distortions from tip vortex interference of the predicted blade loading when compared with lifting-surface calculations.

An example from experimental data (Ref. 27) of the effect of the rotor wake on the pitching moment for the compound configuration of the NASA/Army rotor systems research aircraft is presented in Figure 4. The rotor-on data represent flight at 60 knots forward velocity and show that the rotor induces about an 0.5 pitching-moment coefficient increment. Reference 27 presents other rotor effects including an induced rolling moment with the compound wing, induced directional characteristics on the vertical tail, and interaction with the tail rotors and auxiliary engine jet efflux. Additional experimental investigations (Ref. 28) have been conducted to measure with a laser doppler velocimeter the flow velocities induced by a model helicopter.

3. WAKE/LIFTING-SURFACE INTERACTIONS

Aircraft wings and control surfaces must operate in flow fields influenced by many factors including their mutual interaction. At moderate angles of attack, the wakes generated by lifting surfaces induce twist and camber distributions over the entire aircraft. At high angles of attack, leading-edge vortices and flow separation often occur which can create more severe wake effects. Wake/lifting-surface interactions (Fig. 5) include a variety of aerodynamic situations, such as effects of wings on tails, canards on tails, external stores, engine pylons and nacelles and separated flow from any source. This section will examine wakes which are defined as flows which trail from surfaces or bodies with local velocities less than free-stream velocity.

3.1 Effects of lifting-surface wakes on other lifting surfaces

Traditionally wing wakes induce a downwash angle and local velocity change at horizontal tails. The downwash angle usually changes the tail incidence required for trim while the local velocity change affects the tail area. There are similar effects when canards and wings interact. However, today modern analysis tools make it possible to design particular twist and camber distributions into an aircraft configuration to achieve an optimum drag-due-to-lift efficiency parameter, e.

For the canard-wing planform (Ref. 29) in Figure 6, the effect of wing height on e is presented for positive or negative canard loads and for several canard span to wing span ratios. It is seen from Figure 6 that as canard height is increased an increase in e is obtained for a positive load on the canard and a decrease in e is obtained for a negative load on the canard.

The reduction in drag due to lift from contributions of the canard, strake, and wing camber is presented in Figure 7. The theoretical minimum was predicted with a vortex drag minimization theory (Ref. 29). Data for two cambered wings, in the presence of a canard, designed to have a constant chordwise net pressure distribution, and consequently, a zero leading-edge singularity strength, are given in Reference 29. The design lift coefficients for these wings are 0.35 and 0.70. It is seen in Figure 7 that the theoretical value of minimum drag due to lift is approached at the design lift coefficients for these designs.

There are an infinite number of cambers which will force the viscous drag due to lift to approach the theoretical inviscid minimum at low Mach numbers. The test data shown in Figure 7 were obtained at 0.3 Mach number. As the upper surface approaches a local Mach number of unity, perpendicular to the isobar at or after the crest, the camber which should be used is that which minimizes the occurrence of shock-induced separation. In general, the camber which should be selected is that which minimizes the adverse pressure gradients on the upper and lower surfaces along the whole chord, not just at the leading edge. Forcing the leading-edge singularity strength to be a minimum only minimizes the adverse pressure gradient at the leading edge.

Flow separation can only be prevented by means of camber at a given angle of attack. At the angle of attack where the flow begins to separate, it is best to produce a vortex-type flow separation by means of a strake. This will increase the maximum lift coefficient and produce less drag for a given lift than obtained with two-dimensional type separation. Along with the improved maximum lift coefficient and lower drag due to lift, a nose-up moment is usually obtained with the use of a strake and resulting vortex lift. This nose-up moment can be trimmed with a combination of trailing-edge flap and thrust deflection.

Flow separation represents one source of wakes which can affect nearby lifting surfaces. The subject of flow separation was treated in the AGARD Fluid Dynamics Panel Symposium in 1975 (Ref. 31). The subjects of laminar separation, turbulent separation, and three-dimensional separation were thoroughly discussed. Recent results for subsonic, transonic, and supersonic separated flows were evaluated with an assessment of directions for future research activity. One key conclusion stated that real progress in the field of fluid mechanics demands the existence of a very close relationship between experiment and theory. Furthermore, theoretical solutions should always be carried to a point where detailed numerical calculations become possible. This situation does not exist at the present time.

Currently, there is a limited amount of experimental data for even two-dimensional airfoils with separated flow. An example of available data is an investigation of a GA(W)-1 general aviation airfoil by Wentz (Ref. 32) where detailed measurements were made of separated flow fields on a two-dimensional airfoil at low speeds. A major portion of this work involved development of an appropriate velocity probe for measuring flow magnitude and direction close to the airfoil. This difficulty is greatest in the separated flow regions. Additional experimental work will be needed for multi-element airfoils and for three-dimensional airfoils to validate and improve existing analyses.

The performance of high-lift airfoils involves the effective design of multi-element analysis. Considerable attention to designing favorable interference is needed to alleviate the possible adverse effects of large pressure gradients inducing flow separation on adjacent lifting airfoil elements. A. M. O. Smith presented an excellent survey of high-lift aerodynamics in the 37th Wright Brothers Lecture (Ref. 33). An example of the combined use of analytical and experimental methods for advanced high-lift design is presented in Reference 34. This work used a version of the NASA/Lockheed two-dimensional high-lift flap computer program (Ref. 35) which analyzes multi-element airfoils with a combined viscid-inviscid solution which indicates where separation begins. In Reference 35, it is shown that the leading-edge slat gap and deflection design optimization for lift, which was conducted in the attached flow region, was experimentally shown to also be a valid optimization for maximum lift.

Several analytical methods (Refs. 35 to 37) have been developed for two-dimensional airfoils with various degrees of flow separation represented. The NASA/Lockheed method indicates approximately where flow separation begins and then the computation stops. Bhateley and McWhirter (Ref. 36) require that the user identify the chordwise location of trailing-edge separation and then use the pressure coefficient computed at that location as a constant value from the separation point to the airfoil element trailing edge. Jacob (Ref. 37) also predicts the trailing-edge separation and represents it with a simulated outflow from the airfoil.

The line relaxation finite-difference method developed by Murman and Cole (Ref. 38) solves for the velocity potential. The point of separation is specified, and the pressure in the separation region is calculated. It should be noted that it is possible to couple the inviscid computation with a boundary-layer computation and determine the point of separation by iteration.

Several methods (Refs. 39 to 41) have been developed recently which calculate separated flow about airfoils with the full Navier-Stokes equations or some approximate set of these equations. Also, boundary-layer methods (Refs. 42 to 44) have been applied to the calculation of separated flow.

The methods of Jacob and Bhateley and McWhirter and one version of Barnwell (Ref. 45) employ the empiricism that the pressure is constant on that portion of the airfoil where the flow is separated. It should be noted that this empiricism is consistent with experimental data, which show that the pressure downstream of the separation point has a nearly constant value well below the stagnation value and that upstream of the separation point the pressure gradient is large and positive. It should also be noted that the empircism is consistent with theoretical treatments.

It can be seen that as the Reynolds number is increased, the viscous regions diminish in size, and the fluid speed in the inviscid back-flow region decreases. Thus for large Reynolds numbers, laminar separation can be approximated by an outer inviscid flow and an inner very-low-speed inviscid flow which are separated by a free streamline.

In the case of the method of Jacob, the procedure for determining the pressure level in the separation region is complicated; in the case of the method of Bhateley and McWhirter, the pressure level in the separation region must, in effect, be specified. In both methods, a distribution of vortices is used on the airfoil surface. In the method of Jacob, a distribution of sources is used in the region of separation. Consequently, the separation region is modeled by a region of flow which is emitted at the airfoil surface and which streams downstream to infinity. It should be noted that the source distribution used in a Jacob-type method is not unique, and that the determination of a workable distribution is accomplished by trial and error and can be laborious. In the method of Bhateley and McWhirter, it is assumed that the airfoil terminates at the separation point and does not extend into the separation region. The pressure is calculated for the displacement surface. The shape of this surface at the separation point, which influences the value of the pressure at the separation point, is an input quantity. Consequently, the separation pressure is, in effect, an input quantity. It is simply assumed that the pressure in the separation region is the same as that at the separation point.

Barnwell (Ref. 45) described two inviscid computational simulations of separated flow about airfoils. The basic computational method is based on the line relaxation finite-difference method (Ref. 39). Viscous separation is approximated with inviscid free-streamline separation. The point of separation is specified and the pressure in the separation region is calculated. In the first simulation, the empiricism of constant pressure in the separation region is employed. This empiricism is easier to implement with the present method than with singularity methods. In the second simulation, acoustic theory is used to determine the pressure in the separation region. The results of both simulations are compared with experiment.

In Figure 8, the results of experiment (Ref. 46) and version 1 of the present method for the dependence of the lift coefficient C_L on the angle of attack α are compared. The airfoil is the GA(W)-1 with transition fixed, and the test conditions are $M_\infty = 0.15$ and $R = 6 \times 10^6$. It can be seen from the experimental pressure distributions given in Reference 46 that the flow is separated for angles of attack of 8° and larger and attached for smaller angles of attack. The separation-point locations used in the numerical computations were obtained from the experimental results of Reference 46. It is seen that, given the separation-point location, the present method does a reasonable job of predicting the magnitude and location of the maximum lift coefficient.

There is some work available on the simulation of turbulent boundary-layer separation of multi-element infinite swept wings by Dvorak and Geller (Ref. 47). At the present time, this method is only useful for application to airfoils for which experimental data are available. Further work is needed to develop better empiricism for representing the flow separation region. From this survey, it is apparent that a lot of work is needed before airfoil flow separation is adequately documented experimentally for development of two- or three-dimensional analysis methods. This first step is needed to properly evaluate the effects of flow separation on nearby lifting surfaces.

4. VORTEX/LIFTING-SURFACE INTERACTIONS

Currently two major areas of vortex/lifting-surface interactions are being studied actively in the United States (Fig. 9). The first area deals with separated edge vortices (Ref. 48) such as those generated on leading-edge strakes, high sweep wings, wing tips, and the edge of partial-span flaps. The majority of these effects relate to supersonic aircraft or high performance combat aircraft. The second area deals with wake vortices. In one case, wake vortices may influence aircraft either for close formation flight, for mid-air refueling operations, for agricultural aircraft spray patterns, or for helicopter blade vortex interaction (Ref. 49). In a second case, wake vortices from large transport aircraft are a hazard to following aircraft. This hazard is quite significant in the final approach to landing at an airport and persists for large distances behind the generating aircraft.

4.1 Separated-edge vortex effects on adjacent lifting surfaces

Highly swept, tapered, low-aspect-ratio wings are used for many aircraft designed for high-speed flight. The flow about these slender wings produce well organized separated edge vortices along their leading and side edges as shown in the upper right-hand portion of Figure 10. At low to moderately high angles of attack, these vortices reattach on the upper surface. At very high angles of attack, vortex breakdown can occur. This is characterized by the bursting of the tightly rolled vortex core. When this occurs above the wing surface, lift loss, pressure fluctuations, and general unsteadiness can occur.

Theoretical predictions of the aerodynamic performance of slender sharp-edge delta wings require consideration of nonpotential-flow effects in the form of leading-edge spiral vortices produced by leading-edge separation. These vortices have large effects on the performance characteristics, especially during takeoff and landing or at high angles of attack, and accurate predictions of these effects are possible. Initial theoretical approaches have been based on various mathematical models of the spiral vortices (See Refs. 50 to 54, for example) and have not provided sufficient accuracy because of the difficulty in calculating the size, shape, position, and strength of the primary and secondary spiral vortices and their feeding sheets.

In one of the more effective methods for estimating the lift associated with these vortex flows, Polhamus introduced the concept of the leading-edge suction analogy (Ref. 55). The suction analogy states that for the separated flows situation, the potential-flow leading-edge suction form becomes reoriented from acting in the chord plane to acting normal to the chord plane (a rotation of 90°) by the local vortex action resulting in an additional normal force. (See insert on Fig. 10.) The reasoning is that the force required to maintain the reattached flow is the same as that which had been required to maintain the potential flow around the leading edge.

An application of the suction analogy is shown in Figure 10 for a 75° swept sharp-edge delta wing at a low subsonic Mach number taken from Reference 56. Both lift as a function of angle of attack and drag due to lift are seen to be well estimated by the analogy. Since the original application, the suction analogy concept has been applied to more general planforms. (See Refs. 57 and 58.)

In Reference 59, Lamar demonstrated that the suction analogy was not limited to analysis of leading-edge vortex flows, but could be applied wherever singularities in the potential-flow induced velocities produced an edge force. The aerodynamic characteristics of a representative fighter aircraft is presented in Figure 11 to show the effect of vortex flows on the wing. At a lift coefficient corresponding to a 1-g cruise load factor, the combination of potential-flow theory and leading-edge vortex lift can be seen on both graphs to estimate reasonably well the experimental data of Reference 59. However, at a lift coefficient corresponding to the 7-g maneuvering load factor, it is clear that the theoretical combination underestimates the data. Application of side-edge vortex lift (Ref. 60) can be used to account for this difference.

4.2 Wake vortex effects on trailing lifting surfaces

Large aircraft leave behind them substantial disturbances to the air that may pose a hazard to smaller aircraft entering that airspace. The turbulence in the wake caused by engine exhaust dissipates rather quickly, but the circular motions produced by the wing-tip vortices persist for distances of the order of miles behind the generating wing. During cruise, aircraft can usually be separated laterally and vertically to avoid encountering one another's wake, but near airports the aircraft are usually confined to a relatively few entry and exit corridors, so that the probability of encountering the wake of a preceding aircraft is greatly increased.

In the early 1950's, concern was expressed when the DC-6B was put into operation because it was a new large aircraft. A rather complete analysis of the hazard in the wake of the DC-6B aircraft by Bleviss (Ref. 61) concluded that the hazard is due to the wake vortices and not the "propwash" and that the vortices decay very slowly. The suggested solution was to increase the separation between the aircraft.

The advent of the "jumbo jet," together with the increased traffic load at major airports, has resulted in the wake vortex becoming a significant safety hazard during landing and takeoff. At present, this hazard is still minimized by requiring increased separation between aircraft on landing and takeoff, thereby decreasing the capacity of the airport. This decreased capacity, in itself, becomes a problem due to the increased traffic load which is being placed on major airports. The Federal Aviation Administration (FAA) objective is to increase airport capacity by a factor of two by 1980 and a factor of five by 1995. This increase in capacity must in part come from a reduced separation between aircraft which can be accomplished only when the wake vortex problem is resolved.

In the late 1960's, the Air Force Office of Scientific Research initiated a program of research in aircraft wakes. This program included studies of the formation of trailing vortices, decay and breakup of vortices, interaction with the environment, operational considerations, and experimental techniques. Much of this work was summarized in a Symposium on Aircraft Wake Turbulence (Ref. 62) held in Seattle, Washington, in 1970. The most important practical problem of the symposium was determining the interaction between the organized vortex wake of one aircraft and the flight of another.

An excellent review of the present state of knowledge about vortex wakes is presented in Reference 63. It includes discussions of wake rollup, geometry, instability, and turbulent aging. Also included are a brief review of the persistence of vortices in the atmosphere and design techniques which might be used to minimize the vortex-wake hazard. One early analysis (Ref. 64) was extended by Donaldson (Refs. 63 and 65) to calculate aircraft wake velocity profiles. Another early method (Ref. 66) has been extended (Ref. 67) to reduce some of its numerical instabilities. A recent survey of computational methods for lift generated wakes is presented in Reference 68.

In recent years, the FAA has been working on reduction of the hazard of vortex wakes as a major operational problem, particulary in the approach and landing phase of aircraft operation where increased separation distances severely limits airport capacity. It has been concluded that a decrease in spacing with the present large variation in aircraft size and without a compromise in safety of flight can be accomplished either by locating the hazardous volumes posed by the vortices and directing the aircraft away from them or by changing the lift-generated wake so that the hazardous distance behind the generator is substantially decreased.

The FAA and Transportation Center (DOT) have concentrated their efforts on the development of avoidance systems. An example of this research is the Scanning Laser Doppler Velocimeter (SLDV) System (Ref. 69) which was installed at John F. Kennedy (JFK) International Airport in September 1974. The SLDV, together with several other systems, was put into operation at JFK as part of the FAA's Wake Vortex Avoidance System (WVAS) test program. The WVAS is planned to determine aircraft separation criteria based on aircraft type and airport weather conditions far enough in advance to establish minimum safe landing and takeoff patterns.

NASA is studying means for aerodynamic alleviation of the vortex-wake hazard. A summary of the current status of this program was presented at the NASA Symposium on Wake Vortex Minimization (Ref. 70) early in 1976. It was shown at this symposium that elimination of the wake vortex hazard as a constraint to airport operations by aerodynamic design or retrofit modifications is possible.

This conclusion was obtained from an extensive series of experimental tests conducted by NASA in wind tunnels and towing tanks. The wide variety of proposals for vortex-wake alleviation may be broken into the following categories according to the principal cause advanced by the proposer for their system's success: (1) addition of axial velocity to the vortex core; (2) depletion of axial velocity in the vortex core; (3) addition of vorticity opposing that of the original vortex or tip load modification; (4) introduction of turbulence into the vortex; and (5) span-load variation with time.

After screening a wide variety of vortex-wake alleviation concepts with these tests, several concepts were considered attractive for flight tests. The effects of span-load alteration were examined by varying the deflections of inboard and outboard flaps on a B-747 aircraft. Turbulence ingestion was achieved in flight by mounting splines on a C-54G aircraft and by varying the thrust on the B-747 aircraft. Combinations of span-load alteration were achieved in flight by installing a spoiler on a CV-990 aircraft and by deflecting the existing spoilers on a B-747 aircraft.

As an example of vortex-wake alleviation concepts, the use of existing spoilers on a B-747 aircraft represents one possible method. Wind-tunnel tests (Ref. 71) were conducted using a trailing model mounted at various distances downstream of the B-747 model to measure the vortex-wake induced rolling moment. On the B-747 model, various combinations of in-flight spoilers were deflected ahead of the midspan flaps. The results obtained with the outboard pair of spoilers deflected on both sides of the wing are presented in Figure 12 where trailing wing rolling-moment coefficient is plotted as a function of distance downstream. These results indicate a 40 to 50 percent reduction of induced rolling moment.

Subsequent B-747 aircraft flight tests were conducted to evaluate this use of in-flight spoilers. In the standard approach configuration, the pilot's qualitative separation distance was 7 to 9 nautical miles (Fig. 13, left-hand side). Using the outboard pair of spoilers deflected to 41°, the pilot's qualitative separation distance was reduced to 3 nautical miles. It was found that landing the B-747 airplane with the spoilers extended was accomplished in a relatively straightforward manner. The pilots indicated that the spoilers did not significantly detract from the airplane's landing performance. Further tests will be needed to fully evaluate this device.

5. COMBINED JET, WAKE VORTEX/LIFTING-SURFACE INTERACTIONS

In the reviews of the effects of jets or wakes or vortices on lifting surfaces, many examples (Fig. 14) were found where lifting-surface performance was influenced by two or three of these factors. The purpose of this section is to highlight a few examples of these combined effects. In some examples, these effects will be mutually beneficial. In other cases, they will create the need for airplane design changes to avoid some adverse effects of the complex, combined effects.

5.1 Leading-edge vortex with jets

Several experimental investigations (Refs. 72 and 73) have been done for military combat aircraft applications to show how the leading-edge vortex can be intensified with spanwise blowing. In one case, the spanwise blowing has been combined with upper-surface blowing (Refs. 74 and 75) as shown in Figure 15 for the vectored-engine-over-wing concept.

This work is the result of a joint program with General Dynamics, U.S. Air Force Flight Dynamics Laboratory, and NASA. The curve in Figure 15 for the lift coefficient as a function of angle of attack shows a large lift coefficient increase with upper surface blowing at a momentum coefficient of one. If the nozzle on the side of the engine is opened the engine exit area is reduced to keep the total exit area constant. This nozzle provides spanwise blowing for leading-edge vortex augmentation. When compared with the case of only upper-surface blowing, the data for spanwise blowing with upper-surface blowing (Fig. 15) show a modest lift increment at low angles of attack which increases at the higher range of angle of attack. The lift-drag polar envelope shows that upper-surface blowing alone provides better drag characteristics. The results of this program indicate that selected combinations of spanwise blowing and upper-surface blowing can provide aerodynamic improvements without internal wing ducting or engine bleed complications and a drag polar which approaches the ideal polar over a wide range of angle of attack.

In the transition between hover and wingborne flight, a significant part of the lift of a VTOL aircraft is furnished by direct engine thrust. The high velocity jets issuing from the aircraft at large angles relative to the wing (Ref. 76) produce a complicated flow field which affects the aerodynamic characteristics of the aircraft.

In order to provide a simplified basis for experimental study of this complicated flow field, many investigators have concentrated on the turbulent flow of a subsonic round jet exhausting through a large flat plate into a uniform subsonic crossflow. The path of the jet in the flow field and the pressure distribution on the flat plate have been the subject of numerous investigations in past years (Ref. 77). By comparison, the pair of contrarotating vortices, which consitutes one of the dominant features of the velocity field, has only recently received detailed attention (Refs.78 and 79). This work shows that this combined jet/vortex flow is the major cause of jet efflux induced effects on jet V/STOL aircraft in transition flight. In practical aircraft applications, this jet/vortex system interacts with the vortex wake generated by the aerodynamic lifting surface further complicating the resultant flow field.

The vortex flow pattern from the flap and wing tips during a powered-lift condition are shown in Figure 16. After these vortices merge near the wing, they do not trail straight backward but are drawn in sharply toward the center line of the airplane. At high angles of attack, such as shown in the drawing, the rearward tail (see Fig. 17) enters a region of powerful vortex flow, and the result is a serious loss of stability. The high foward tail (fig. 17), however, would be farther from the more intense parts of the vortex flow, and would retain its stabilizing effect in spite of its shorter moment arm.

The effect of these powered-lift vortices on longitudinal stability is shown in Figure 17 where pitching-moment coefficient is plotted as a function of angle of attack for a high momentum coefficient. The tail-off data show the expected large nose-down, unstable moment variation. The high rearward tail provides a small contribution to stability below 12° angle of attack, but the contribution becomes unstable at high angles of attack as the trailing vortices intersect the tips of the tail surface. When the tail is moved forward, its contribution to stability is increased throughout the range of angle of attack.

The helicopter provides several examples of combined jet, wake, and vortex interaction with lifting surfaces. For example, the wake from the fuselage reduces empennage effectiveness which is further impacted by the propulsive efflux from both the main and tail rotors. The combined effects make helicopter performance analysis difficult unless appropriate experimental data are available from complex model tests or from flight tests.

6. CONCLUDING REMARKS

This paper reviews a number of aspects of the effects of jets, wakes, and vortices on lifting surfaces for a variety of aerodynamic situations. The intent of the paper is to highlight representative work related to this subject without pretense to being a complete, exhaustive compilation of research activity. It shows that lifting-surface performance can be significantly affected by jets, wakes, and/or vortices.

Aircraft wings and control surfaces must operate in flow fields influenced by many factors including their mutual interaction. At moderate angles of attack, the wakes generated by lifting surfaces induce twist and camber distributions over the entire aircraft. At high angles of attack, leading-edge vortices and flow separation often occur which can create more severe wake effects. Several examples of current work are presented.

Throughout the angle-of-attack range, there are also propulsion flows. Their significance depends on the aircraft configuration and thrust level. STOL, V/STOL, and military combat aircraft must be designed to take advantage of these flows to satisfy their performance requirements. Current prediction methods and illustrative experimental data are presented.

During aircraft operations near terminals, the wakes of large jet aircraft pose a significant hazard to any smaller aircraft that follow. A summary of the large current effort in this area shows the status of this work and indicates hope for aerodynamic methods which reduce operating problems.

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CRUISE

- WING
- TAIL

LOW SPEED

- POWERED-LIFT
- PROPELLER SLIPSTREAM
- JET VTOL
- ROTOR

Figure 1. - There are jet/lifting-surface interactions in both cruise and low-speed flight.

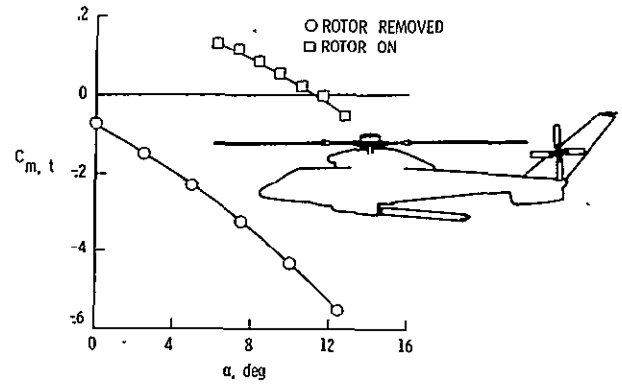

Figure 4. - The effect of rotor efflux on the pitching-moment increment from the horizontal tail.

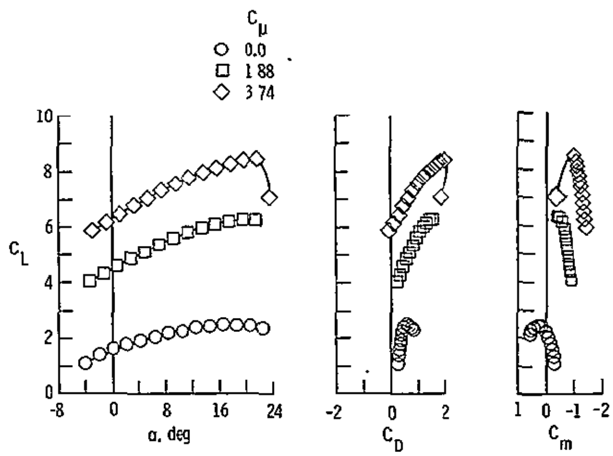

Figure 2. - A typical example (externally blown flap) of the effect of powered lift on aircraft aerodynamics.

WING ON TAIL

- q-EFFECT
- INDUCED DRAG

CANARD ON WING

EXTERNAL STORES

ENGINE PYLONS AND NACELLES

SEPARATED FLOW

- HIGH α
- FLAPS

Figure 5. - Major wake/lifting-surface interactions include a variety of aerodynamic situations.

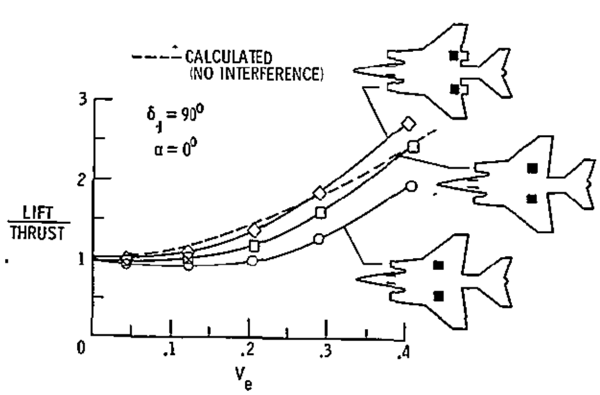

Figure 3. - For V/STOL aircraft the location of deflected lift/cruise engine nozzles with respect to the wing trailing edge strongly influences the jet/lifting-surface interaction.

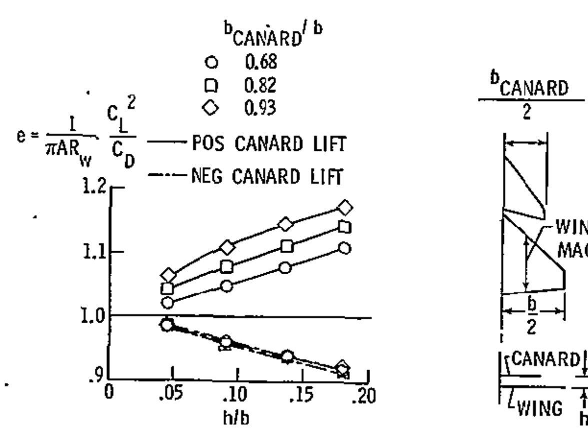

Figure 6. - Potential-flow interactions of a canard on the wing can strongly influence the drag-due-to-lift efficiency parameter.

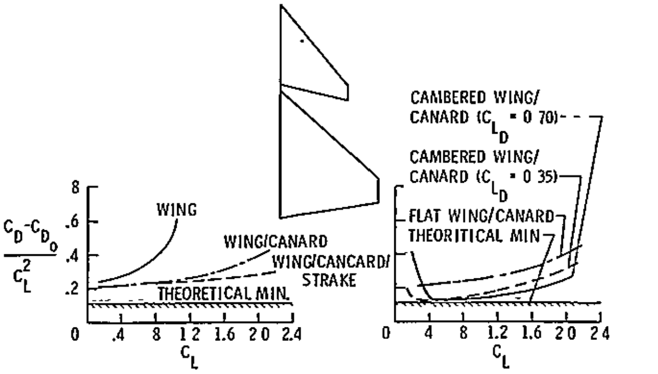

Figure 7. - The viscous interaction among wing, canard, and strake can also stronly influence the drag-due-to-lift efficiency parameter.

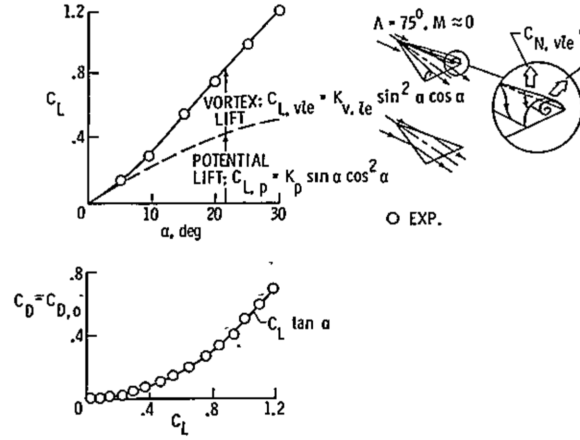

Figure 10. - Hignly swept, tapered, low-aspect-ratio wings produce well organized separated-edge vortices which increase lift coefficient especially at high angles of attack.

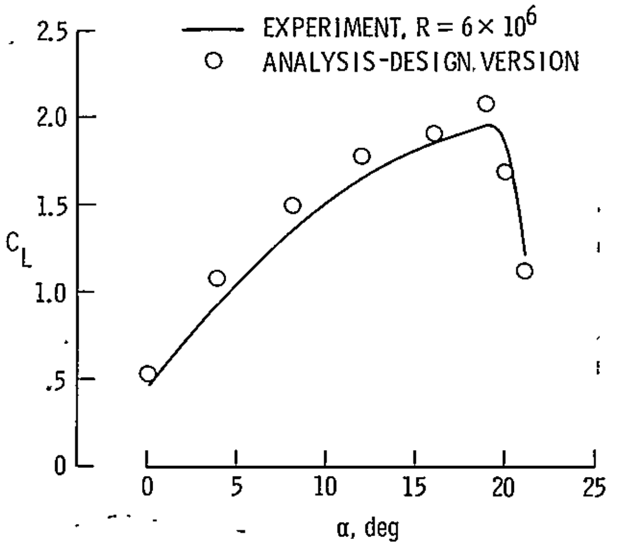

Figure 8. - An example of good agreement between theory (Ref. 46) and experiment for two-dimensional airfoil (GA(W)-1) stall. This comparison required knowledge of the separation point location.

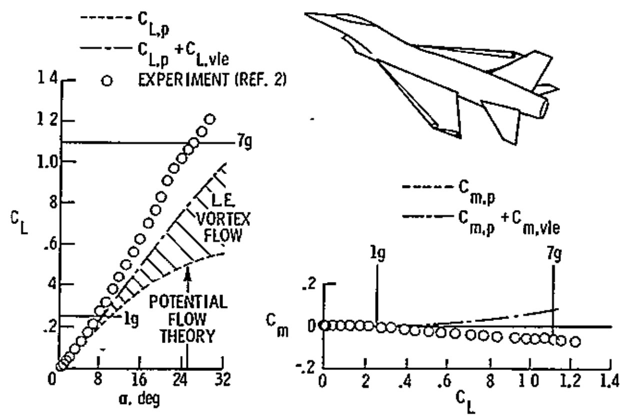

Figure 11. - The effect of separated-edge vortex flows on representative fighter aircraft involves side-edge vortices as well as leading-edge vortices.

SEPARATED EDGE VORTEX

- STRAKE
- HIGH SWEEP WING
- WING TIP
- FLAP EDGE

WAKE VORTEX

- NEAR FIELD
- FAR FIELD

Figure 9. - Two major areas of vortex/lifting-surface interactions are separated leading-edge vortices and trailing-wake vortices.

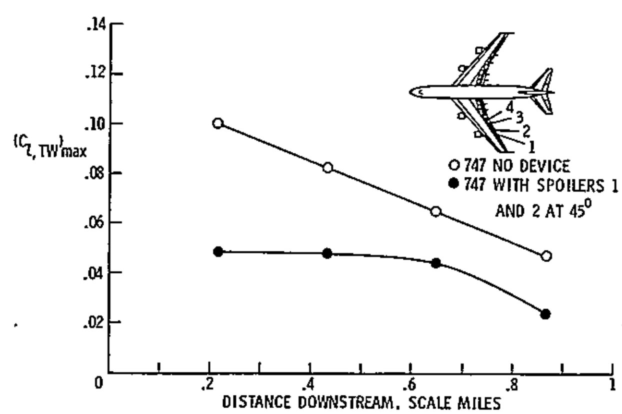

Figure 12. - The rolling moment induced on a trailing aircraft can be reduced by deflecting in-flight spoilers on a Boeing 747 transport aircraft.

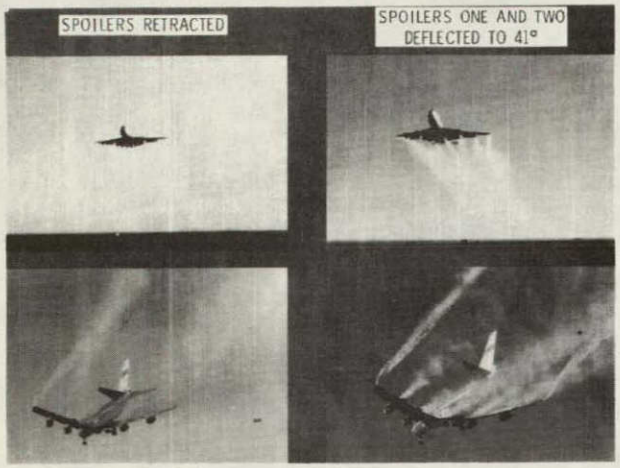

Figure 13. - The beneficial effect of in-flight spoilers on a Boeing 747 aircraft is illustrated by smoke-flow patterns from flight tests.

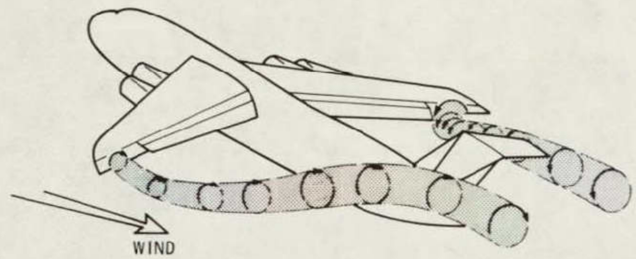

Figure 16. - The combined effects of externally blown flap powered-lift and the vortices from wing tips and flap edges produce a strong wake vortex interaction with the horizontal tail.

LEADING EDGE VORTEX

- WITH DEFLECTED JET
- WITH SPANWISE BLOWING

LIFTING JET/VORTEX

PROPOLSIVE LIFT WAKE

- WITH FLAP EDGE VORTEX

ROTOR WITH FUSELAGE WAKE

Figure 14. - The combined effects of jets, wakes, and/or vortices on lifting surfaces can be either beneficial or adverse.

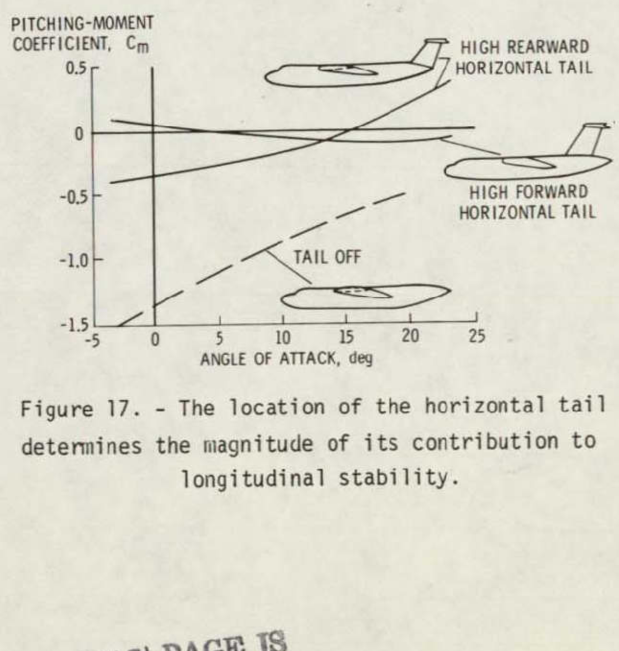

Figure 17. - The location of the horizontal tail determines the magnitude of its contribution to longitudinal stability.

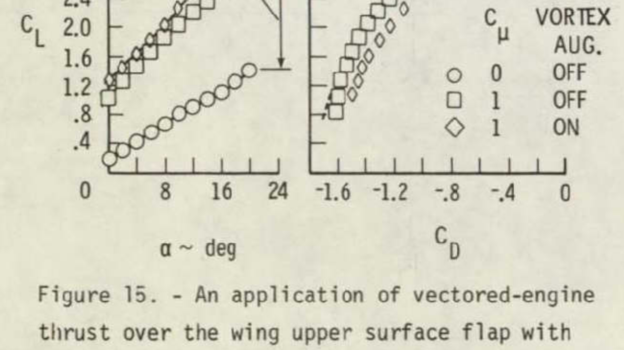

Figure 15. - An application of vectored-engine thrust over the wing upper surface flap with vortex augmentation using spanwise blowing.

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