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On Issues Concerning Flow Separation and Vortical Flows in Three Dimensions

David J. Peake and Murray Tobak

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SUMMARY

This review provides an illustrated introduction laying the knowledge base for vortical flows about three-dimensional configurations that are of typical interest to aerodynamicists and researchers in fluid mechanics.

The paper then compiles a list of ten issues, again in illustrative format, that the authors deem important to the understanding of complex vortical flows. These issues and our responses to them provide, it is hoped, a skeletal framework on which to hang the ensuing conference proceedings.

1.0 INTRODUCTION

About typical flight vehicles, three-dimensional (3D) flow separations emanating from separation lines oblique to the general flow direction tend to roll up into tightly coiling vortex motions. One readily familiar example is the trailing-vortex system behind a high-aspect-ratio lifting wing, where the separation lines occur at the wing tips and extend around and along the trailing edges. Even on this simple configuration, when flaps are deflected the ensuing vortical wake is very complex because of a multitude of additional separations located at the side edges of the flap components.

Associated with the use of a large sweep angle on a wing, often coupled with a leading-edge extension, 3D vortical flows generated ahead of the trailing edge, at or near the leading edge itself, have become increasingly evident. Such leeside flows are usually well-ordered structurally. As a result, designers of combat aircraft and missiles have sought to exploit these axial vortex motions to good effect in meeting speed and maneuver requirements.

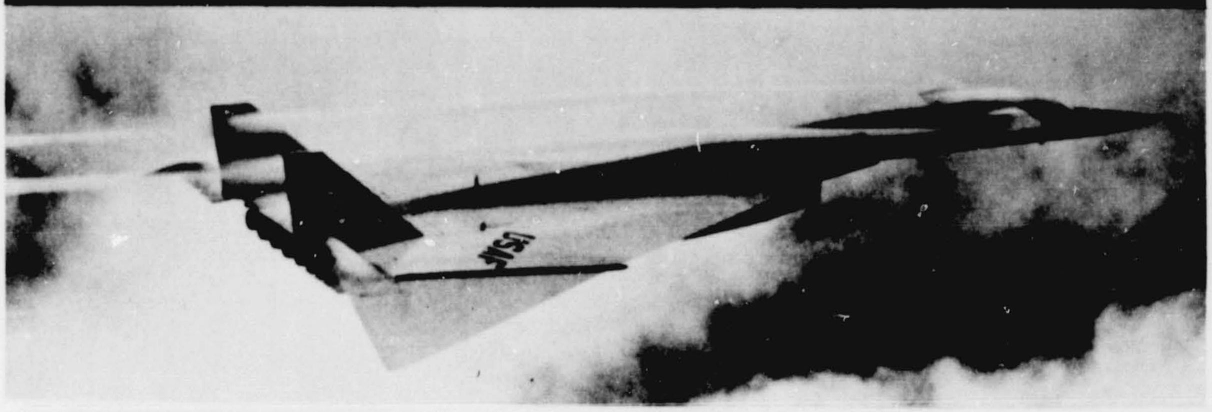
At this time, our understanding of such flows remains essentially qualitative. For particular configurations like the slender wing, flow separations are controlled in the sense that separation lines are fixed at the sharp leading edges, and from the results of many experiments we now possess a fine knowledge of the flow field. In fact, the study of this flow example over the last thirty years has allowed us to extrapolate our findings and appreciate the physics of 3D separations materializing on many other bodies at high angles of attack. Two phenomena significantly restricting the use of vortical flows, however, are the readiness of leeward vortices to develop asymmetrically (particularly those from slender forebodies), or to develop spiral or axisymmetric modes of breakdown. A direct result of vortex breakdown is aerodynamic buffet, where the intensity builds up as the vortex breakdown point moves forward from the trailing edge (as angle of attack increases further) and affects a significant surface area of the wing.

Asymmetry and breakdown are frequently encountered together when a fighter airplane flies under conditions of high angle of attack with sideslip. When the vortical flow is antisymmetric, large side forces and yawing moments may be generated. These moments may be unsteady, and they may be larger than counteracting moments available from the maximum deflections of the control surfaces. Moreover, there may be additional constraints of low observable technology and V/STOL (or STOVL) capability imposed, whereby propulsion-system inlets may be immersed in the leeside vortical wake causing a major impact on the distortion levels in the internal-flow ducting. The control of the development of the leeward vortex wake is hence crucial to flying capably at very high angles of attack under controllable and stable conditions.

Other specialized vehicles, such as rotorcraft, are flying with parts of the airframe immersed in heavily interacting vortical flow fields from the rotor, throughout the entire flight envelope. One concept under development, the tilt-rotor aircraft, utilizes an innovative propulsion system that combines the benefits of high-speed forward flight (with the rotor axes pivoting to near horizontal) with V/STOL capability (the rotor axes close to vertical). In the flight transitional phase of rotating the thrust vector, the vortical wakes from the rotors may have a large impact on tail surfaces, if improperly positioned.

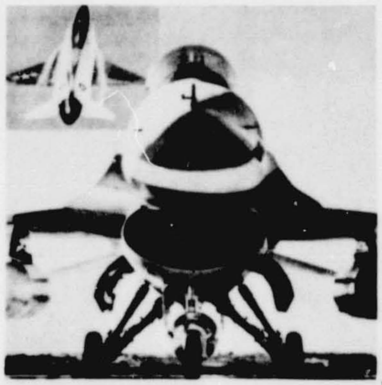
The following photographs (Figs. 1-22) vividly illustrate these introductory remarks.

3-D FLOW SEPARATIONS AND ENSUING VORTICAL MOTIONS OCCUR ON ALL LOW-ASPECT RATIO VEHICLES AT CRUISE . . .



. . . WHEN MANEUVERING . . .

F1



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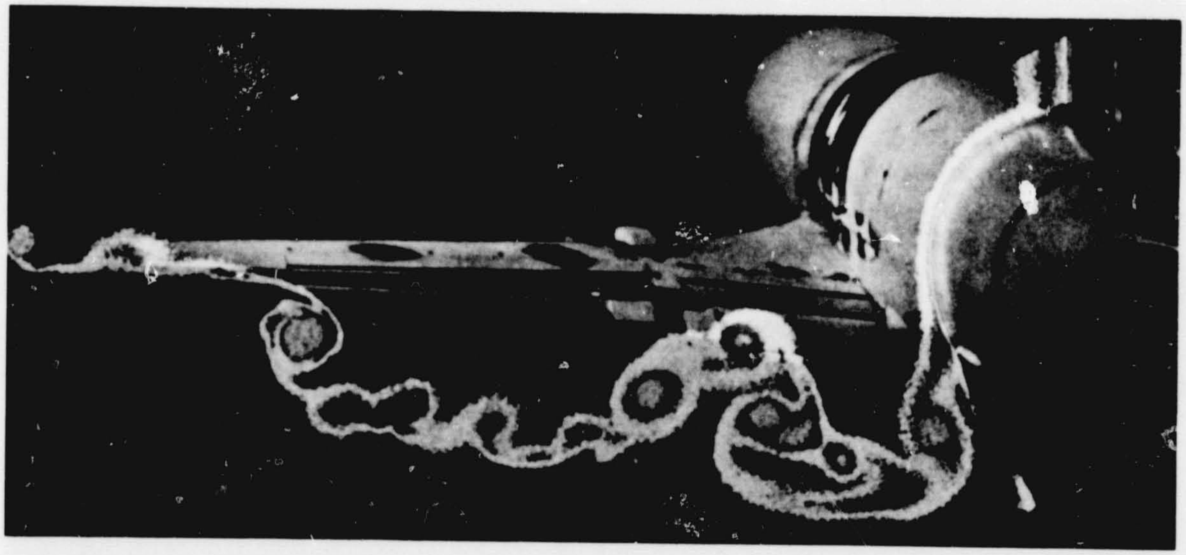

PRODUCING A COMPLEX VORTICAL WAKE

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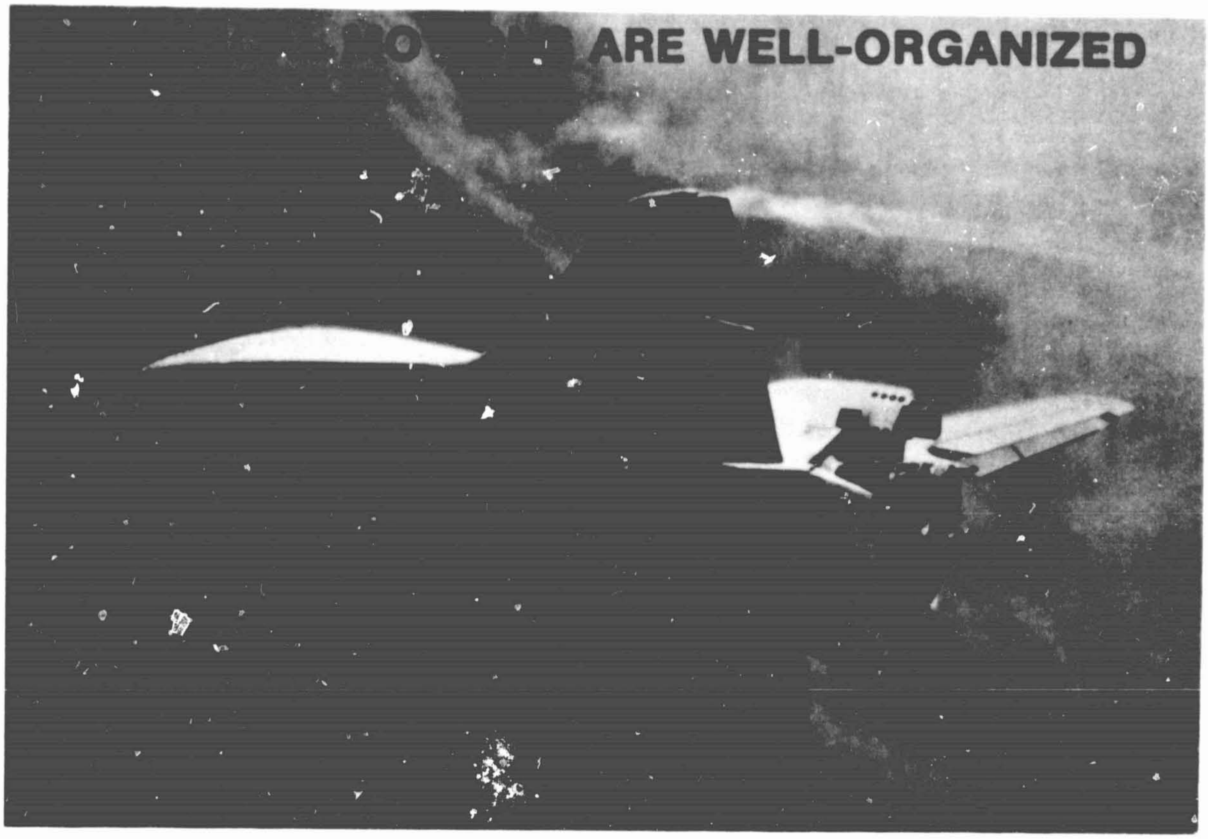
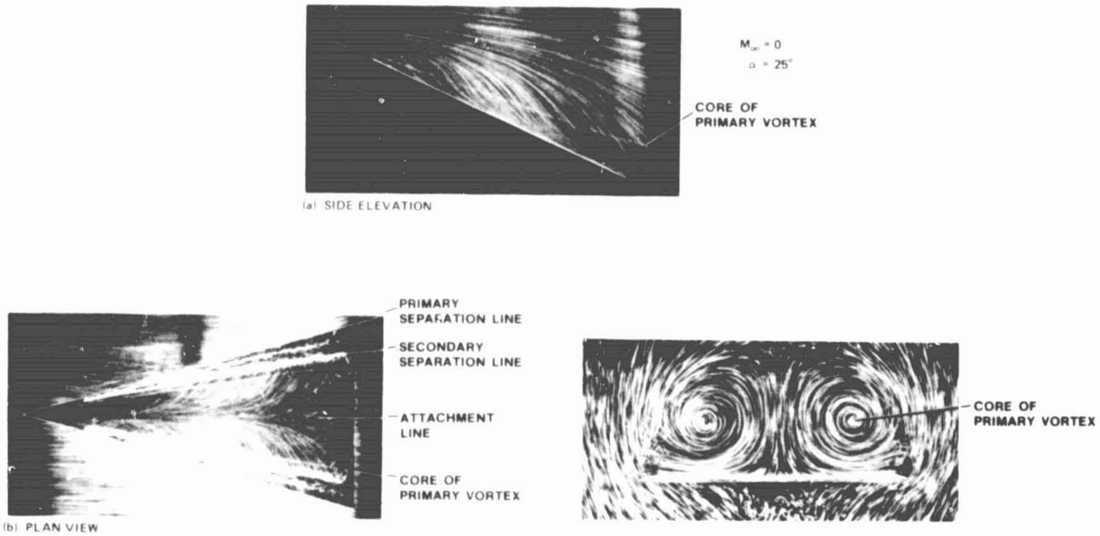


F6

ROLLED UP AND STEADY IN THE MEAN . . .



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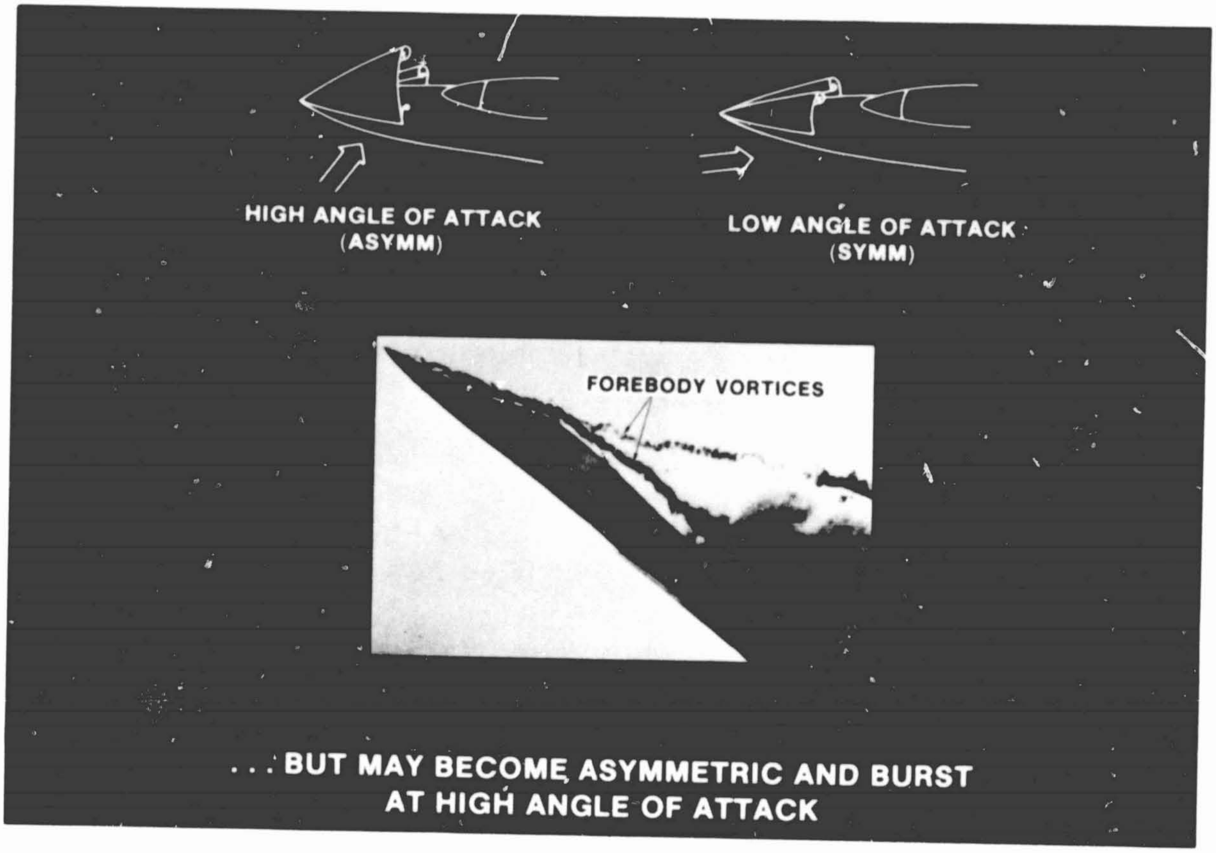

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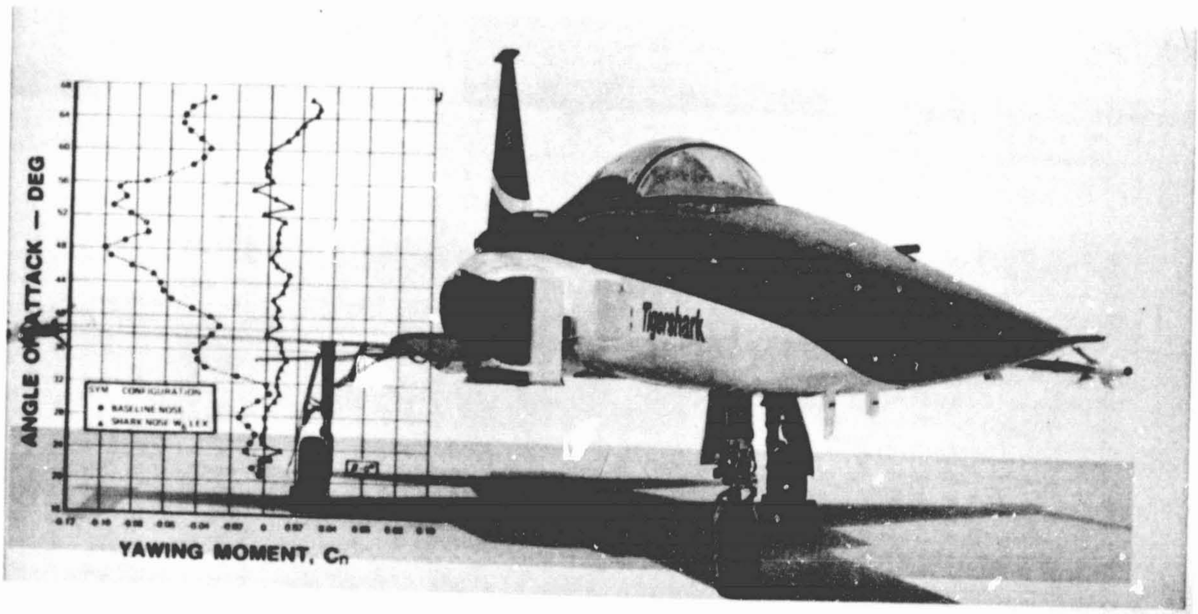
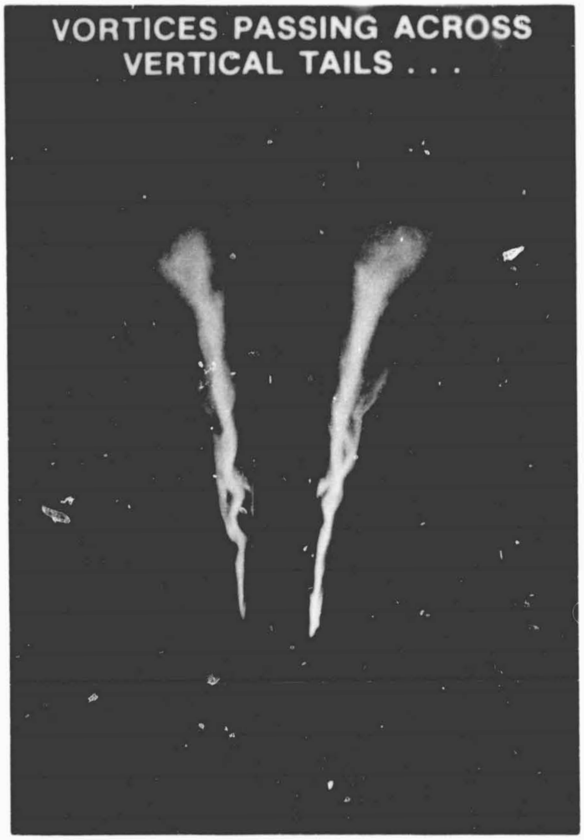
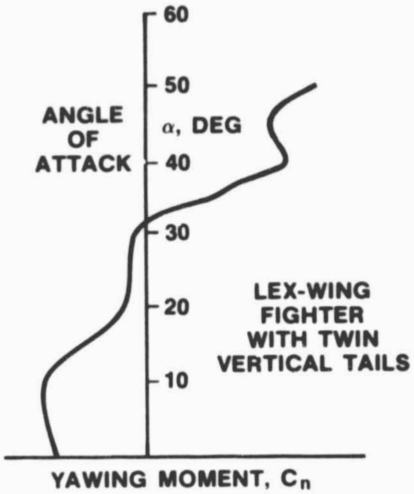
SUBSTANTIAL YAWING MOMENTS RESULT





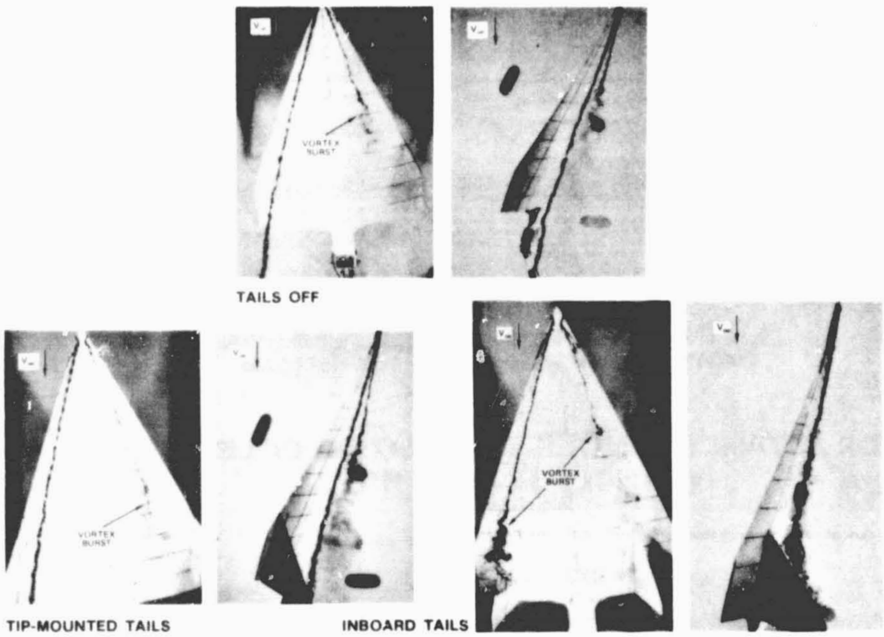
F10

. . . CAN PROVIDE UNSTABLE BREAKS IN YAWING MOMENT DATA



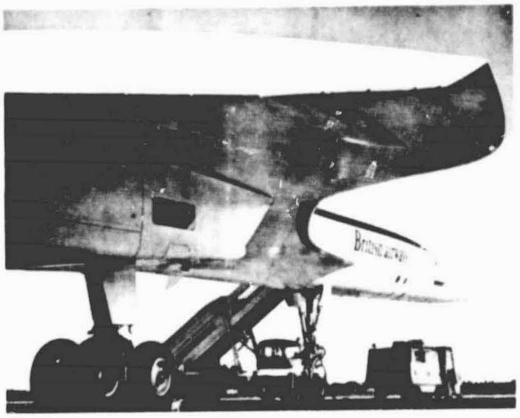
F11

POSITION OF VERTICAL FIN(S) INFLUENCES VORTEX BURST POSITION UNDER COMBINED ANGLE-OF-ATTACK AND SIDESLIP CONDITIONS



F12

PREFER FIXING SEPARATION LINES AT SALIENT EDGES FOR CONTROLLED SEPARATION AND PREDICTABLE FORCE AND MOMENT CHARACTERISTICS . . .



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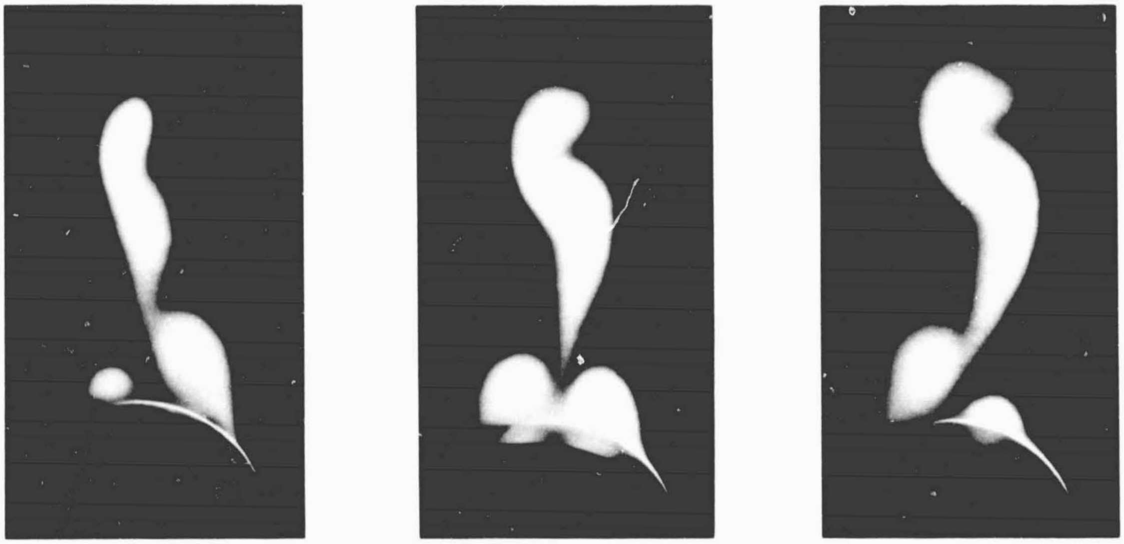

CONE, $\alpha/\theta_C = 3.3$, $C_\mu = 0.003$, $M_\infty = 0.6$
CROSS-SECTION VIEWED FROM DOWNSTREAM

. . . OR ACTIVELY CONTROL ORIENTATION OF LEESIDE VORTICES BY BLOWING

F14

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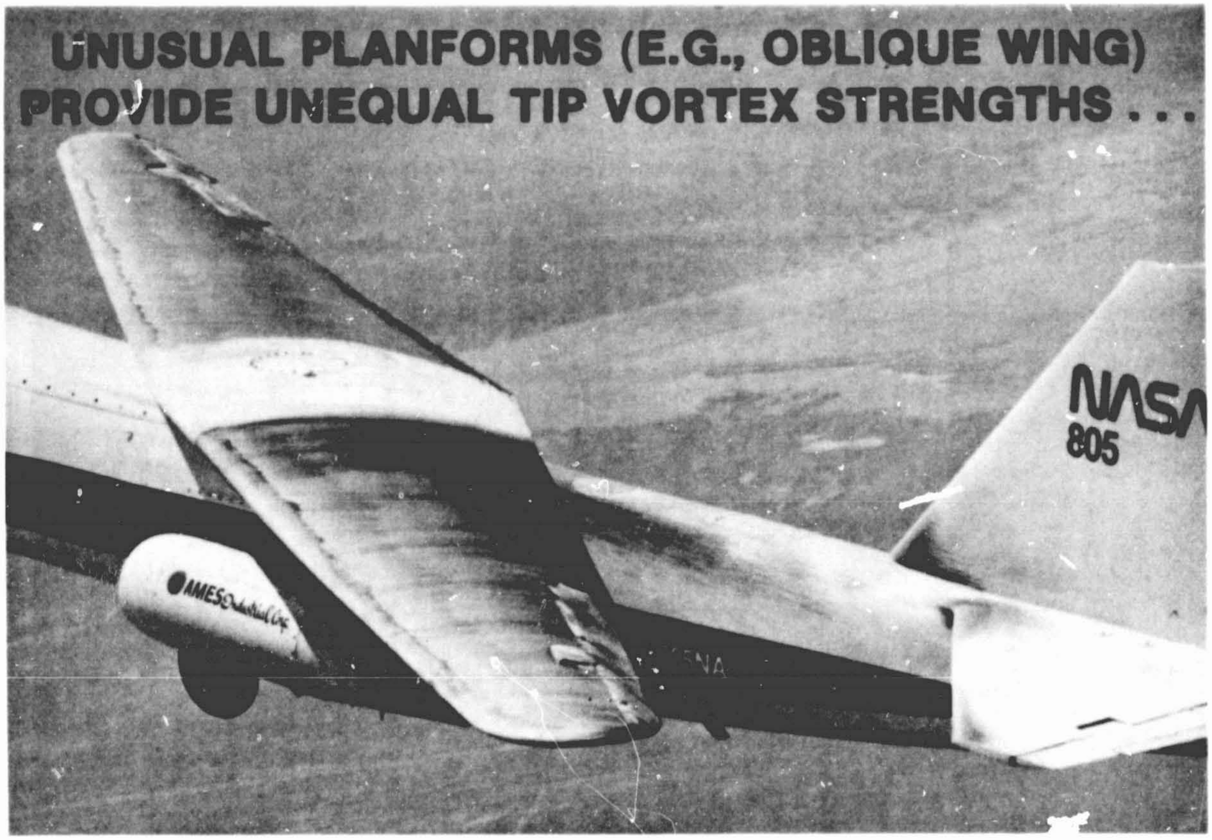

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. . . OR MORE ROTORS, POTENTIALLY CAUSING
BUFFET AND VIBRATION PROBLEMS

F17

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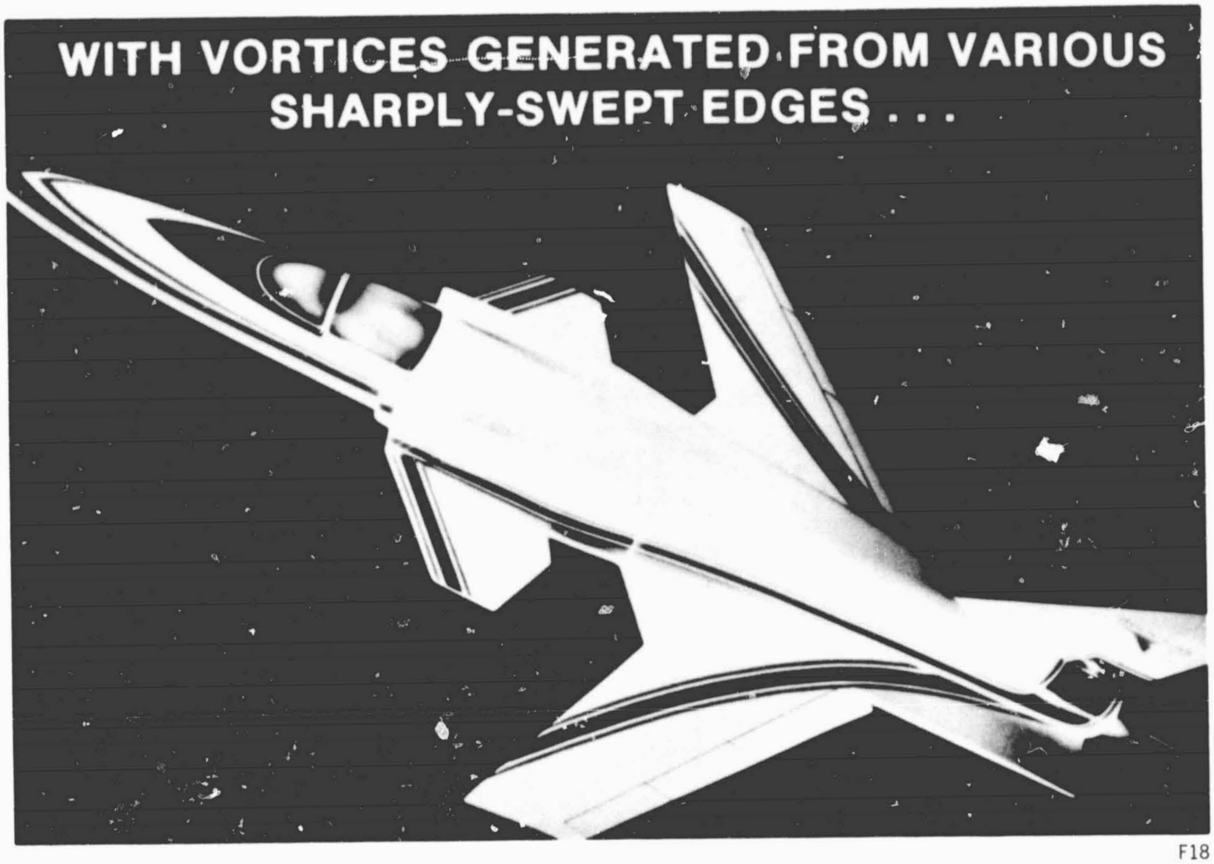

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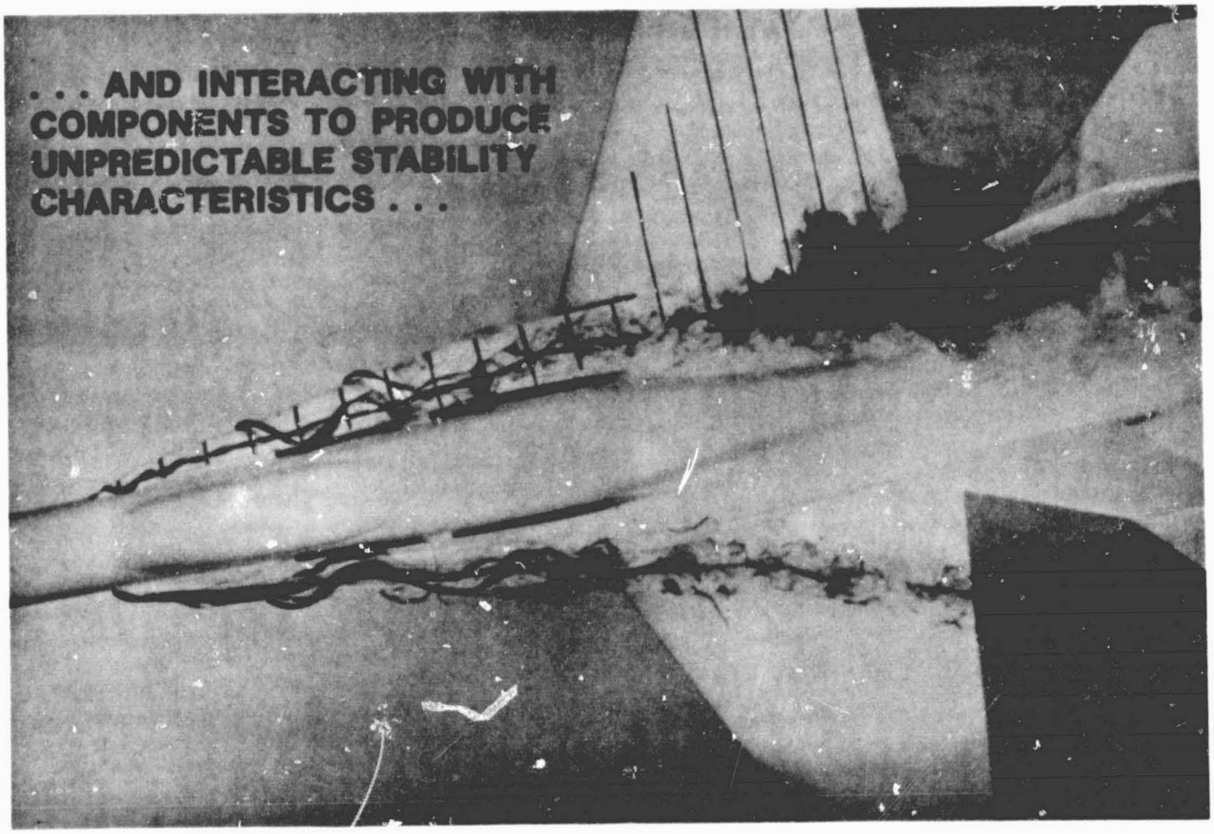
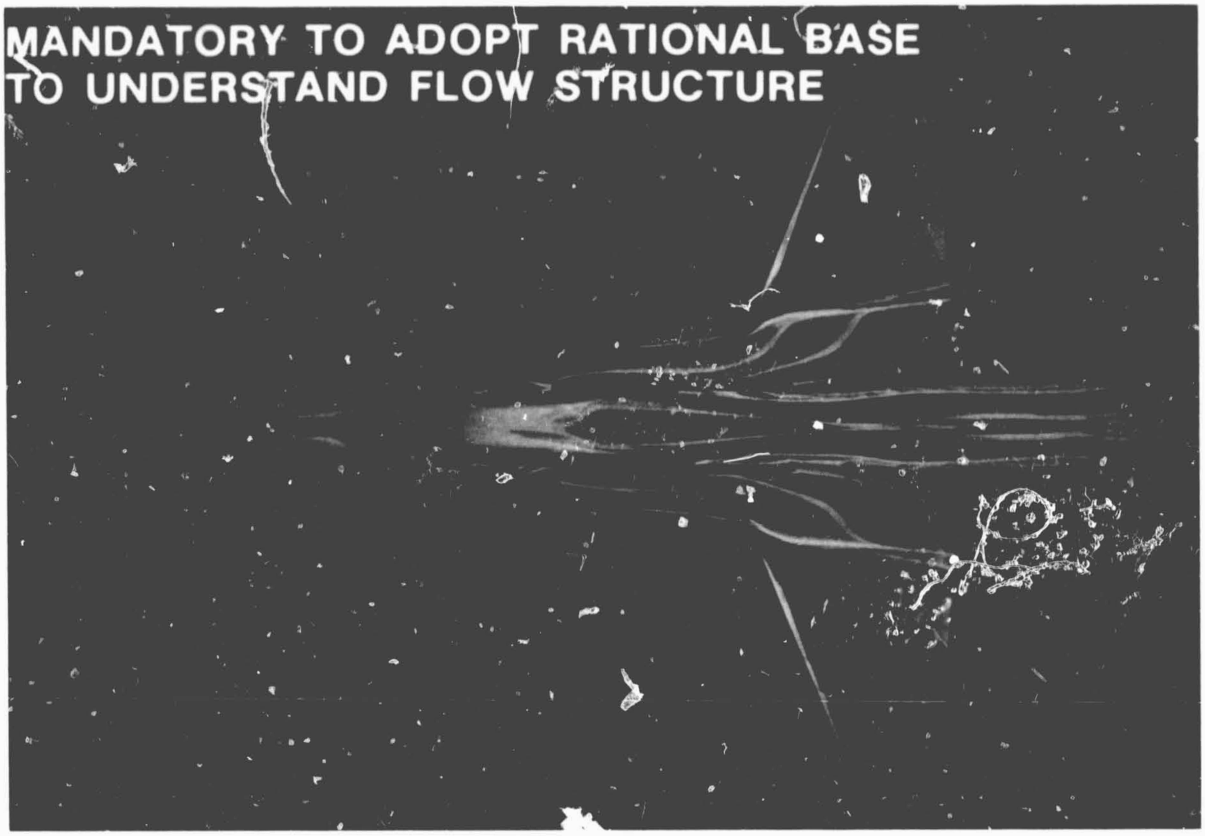
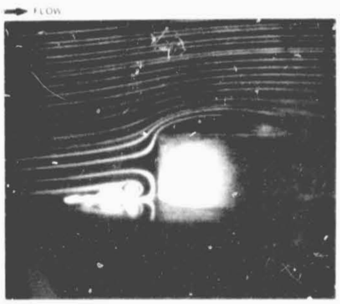




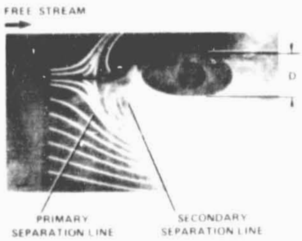
F20

F21

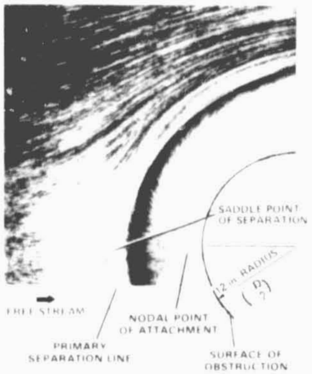
HYPOTHESIZE MATHEMATICAL FRAMEWORK OF CONTINUOUS VECTOR FIELDS (E.G., STREAMLINES IN FLOW AND SKIN-FRICTION LINES ON BODY) IN ASSOCIATION WITH LIMITED NUMBER OF (ZERO VELOCITY OR ZERO SKIN-FRICTION) ANALYTIC SINGULAR POINTS



SMOKE FLOW ABOUT OBSTACLE



WATER TUNNEL



WIND TUNNEL

F22

ISSUES

Having presented a foundation for where vortical flows are important in aerodynamic design, we now present some pertinent issues concerning our knowledge and understanding of 3D, viscous vortical flows. For instance:

1. Do we have an unambiguous definition of separation in three dimensions?

2. Do we understand the structure and mechanisms of separation and the ensuing coiled-up vortical motions?

3. Is it possible to formulate a principle that will distinguish between the scale of vital and unimportant organized vortical structures?

4. Can we exploit the well-organized vortex motions for significant benefit when they are stable?

5. Do we understand the instability mechanisms leading to vortex breakdown and leeside wake asymmetries at high angles of attack?

6. Do we understand the implications of vortices interacting with local flow fields about the wing and tail surfaces?

7. Can we exercise control over these interacting vortical flow fields?

8. Can we use the Navier-Stokes equations, assumed to govern fluid motion, to compute vortical flows about complex aerodynamic configurations at high angles of attack?

9. If not, with appropriate simplifications of the Navier-Stokes equations, and with our current understanding of modelling turbulence, are we able to compute vortical flows about chosen aerodynamic components at high Reynolds numbers?

10. Can modelling the vortical flows by essentially inviscid approaches provide us with satisfactory insight into the flow physics?

Let us now attempt to address each of these issues in turn. In so doing, we hope to provide some responses that will provoke thoughtful reflection and spark additional needed research, both experimental and computational, in using 3D vortical flows to maximum benefit in rational aerodynamic design. Strong consideration must be given to understanding the mean and fluctuating 3D flow structure and how the vortices can be controlled actively or passively.

ISSUES

- **DO WE HAVE AN UNAMBIGUOUS DEFINITION OF SEPARATION IN THREE DIMENSIONS? YES — IF A SEPARATION LIN[illegible]SIDERED ALWAYS TO EMA[illegible]OM A SADDLE POINT.**

F23

Complications arise, however, because flow configurations exist where the conditions for 3D separation appear to be present: skin-friction lines on the body surface converge onto a particular line and, in cross-flow planes, streamlines corresponding to trajectories of the velocity components in these crossflow planes roll up around what appear to be vortex cores. But within the limits of numerical or experimental resolution, the particular skin-friction line on which others converge, does not appear to emanate from a saddle point. Frequently, it appears to emerge from the region of the attachment node (i.e., stagnation point) on the nose of the body. An appropriate example is offered for consideration in Fig. 24, where both primary and secondary separation lines on the leeside of a missile body, obtained on a surface oil-flow pattern, can be considered continuously traceable to the stagnation point. Nevertheless, the eruption of fluid away from the body is confined to those areas downstream of which we first picture the very rapid convergence of skin friction lines, i.e., on the cylindrical afterbody.

Indeed, the question of an adequate, yet convincing, description of 3D separated flow arises with especial poignancy when one asks how 3D separated flow patterns originate and how they succeed one another as the relevant parameters of the problem (e.g., angle of attack, Mach number, and Reynolds number) are varied. In a past essay (Refs. 1 and 2) we proposed to answer this question by placing an extension of a hypothesis of Legendre (Ref. 3) that skin-friction lines comprise a continuous vector field, wherein the singular points of the field can be categorized mathematically, within a framework broad enough to include the notions of topological structure and structural stability coupled with arguments from bifurcation theory. From this rational framework emerged the concepts of local and global separation (again, see Refs. 1 and 2) wherein a separation line was considered as starting at a nodal singular point or a saddle singular point, respectively. The local concept, in fact, implies that when the separation line appears, no new singular points form on the surface or in the flow field to alter the topology. Conversely, the development of a global separation line is connected categorically with the appearance of a new saddle/node pair on the surface and a new 3D singular (zero-velocity) point in the external flow.

Upon admitting, however, that no computational or wind-tunnel experiments of which we are aware give incontrovertible evidence in support of the absence (or the presence) of saddle singular points originating at lines of local separation (in contrast to clear evidence of a saddle/node pair commencing at a global horseshoe shaped separation line), we may perhaps offer an inference from a knowledge of the structure of the external flow in the case of local separation.

Matters are clarified if we accept the existence of a coiling vortical motion downstream (we use Fig. 24 once more to aid the discussion), where the 3D separation lines are pronounced. There, a particular streamline in the external flow is along the axis of the core of the rolled-up fluid. Just as in the case of a global separation, we can form a stream surface which includes this particular streamline in the external flow and the skin-friction line on the surface which has become the line of separation. We can then trace the paths of these two particular lines upstream, and it is clear that the core streamline will be in close proximity to the surface as the nose is approached. The question of the origin of the local separation then reduces to the behavior of the stream surface in the immediate vicinity of the nodal point of attachment at the nose. The problem of resolving the flow detail at the nose forces us to consider two alternative possibilities: either the core streamline passes upstream to infinity, in which case the separation is indeed local; or it terminates in a focal singular point in the flow or on the surface, in which case the line of separation would originate at a saddle point and the separation is global. We argue that inasmuch as we have been able to single out these lines, each must have a special property, which we suggest manifests itself by origination at focal and saddle singular points.

We are suggesting, then, that if a coiling vortex-type flow is admitted downstream, the core streamline must emanate from an upstream singular point, no matter how obscured the singular point may be by a lack of

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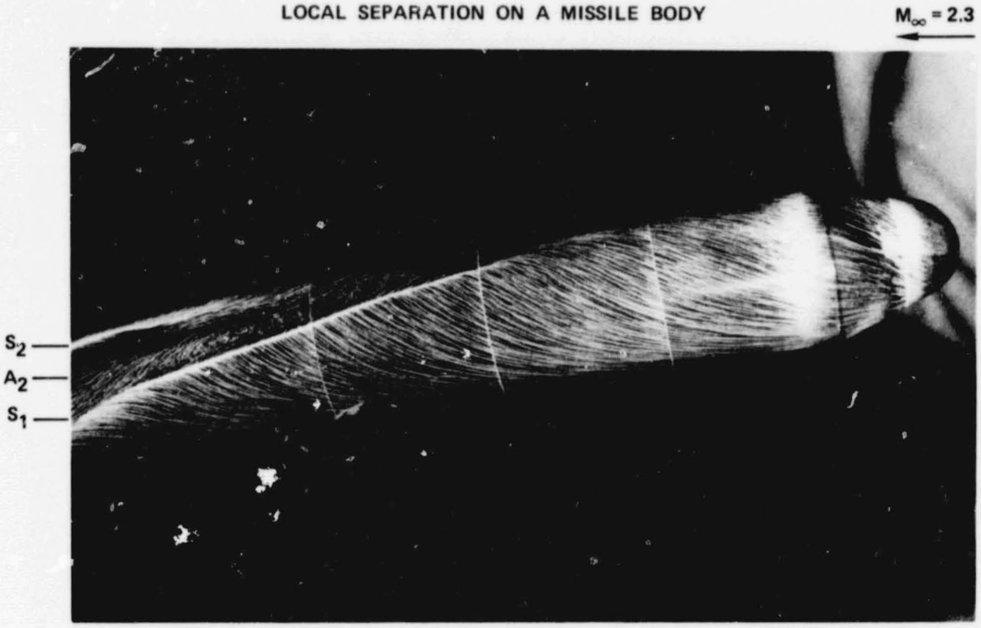
LOCAL SEPARATION ON A MISSILE BODY



(a) SIDE ELEVATION, $R_{L_\infty} \sim 10 \times 10^6$, $R_D = 1.3 \times 10^6$

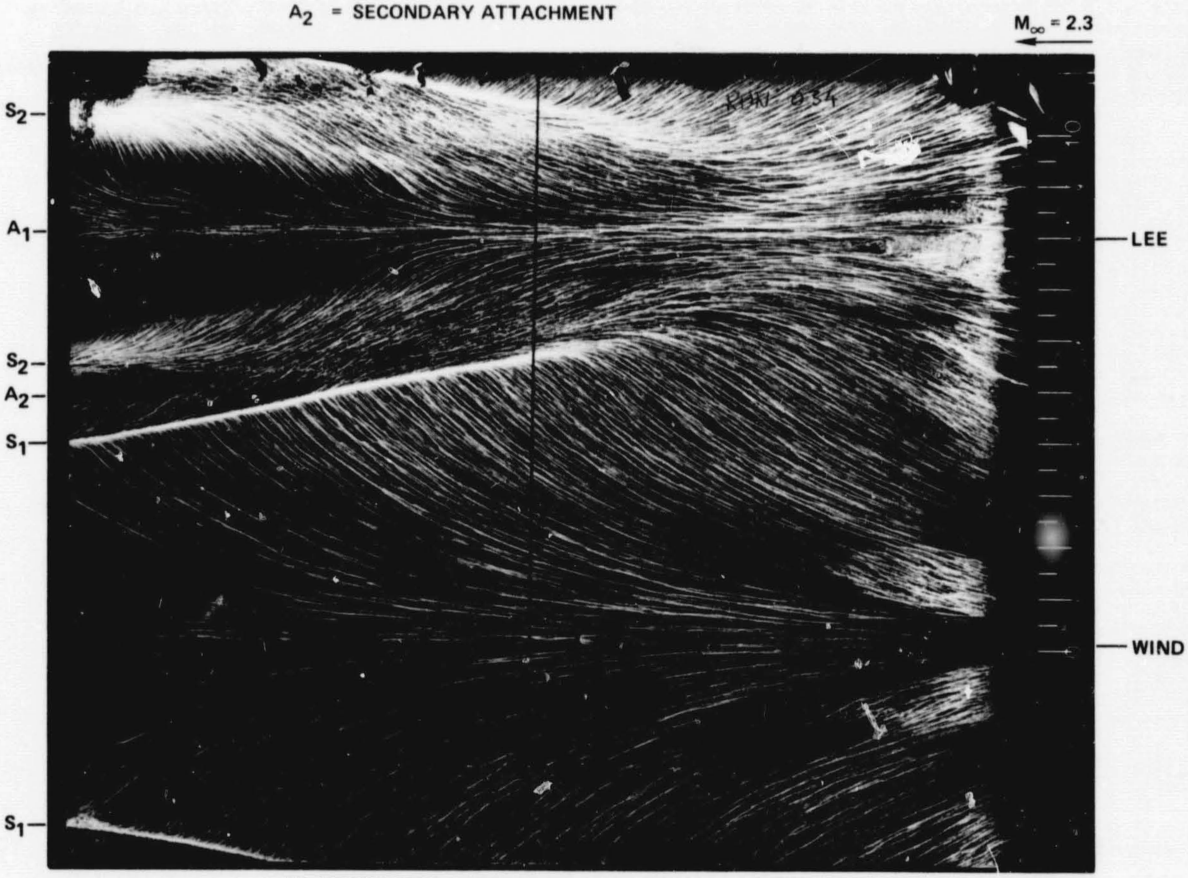
LENGTH, L = 38.2 cm (15 in.); D = 5.0 cm (1.97 in.)

S_1 = PRIMARY SEPARATION OF BOUNDARY LAYER DEVELOPING FROM WINDWARD GENERATOR

S_2 = SECONDARY SEPARATION

A_1 = PRIMARY ATTACHMENT LINE

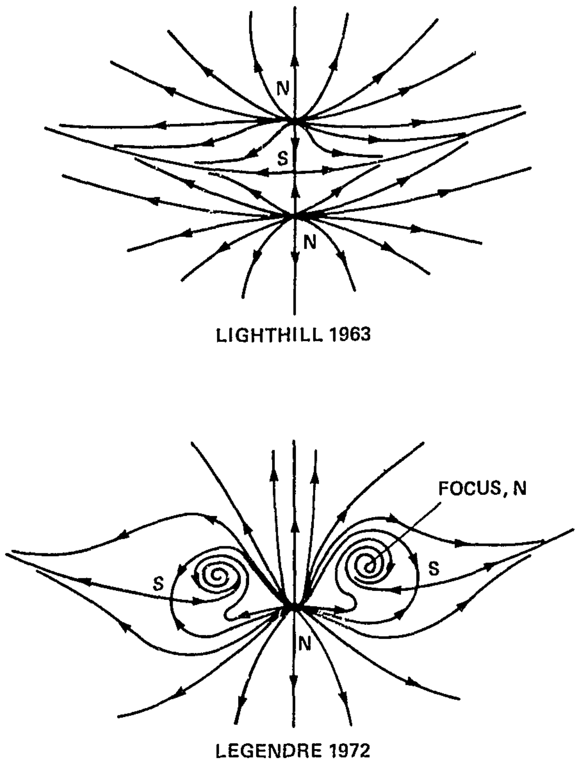
A_2 = SECONDARY ATTACHMENT



(b) UNWRAPPED SURFACE OF CYLINDRICAL AFTERBODY, $R_{L_\infty} \sim 10 \times 10^6$, $R_D = 1.3 \times 10^6$

F24

resolution in numerical and wind-tunnel experiments. Under these circumstances, we must allow a combination of saddle/node singular points (see Fig. 25) in the stagnation region at the nose not unlike the choice of patterns proposed very much earlier by Legendre (Ref. 3) and Lighhill (Ref. 4). This argument, if acceptable, would lead us to favor the second alternative, which suggests that all 3D separations where coiling vortex motions exist are global events (see also Legendre, Ref. 16).



F25

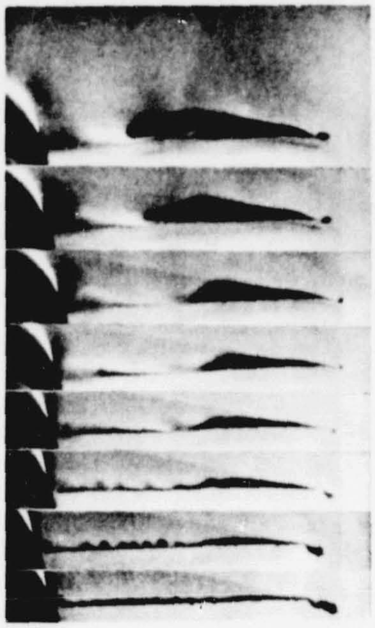
ORIGINS OF GLOBAL SEPARATION

F26

We have a good understanding in mean-flow terms in that we know how to draw topological structures of separated flows and we can envision how the structures manage to undergo topological changes with variations of the governing parameters (e.g., angle of attack). We do not yet have a firm grasp of the relation between structural features and physical quantities such as, e.g., surface pressures, turbulence quantities, etc. We do not yet know how to predict conditions for the emergence of singular points or for their subsequent changes in number and form.

ISSUES

- IS IT POSSIBLE TO FORMULATE A PRINCIPLE THAT WILL DISTINGUISH BETWEEN THE SCALE OF **VITAL** AND **UNIMPORTANT** ORGANIZED VORTICAL STRUCTURES? **UNKNOWN AT THIS TIME**



FLOW BEHIND CAMBERED DELTA WING AT M_∞ = 1.88

F27

One of the several processes of transition is frequently characterized by the appearance of arrays of vortices with axes slightly skewed from the local external flow direction when the body is at low angle of attack. In Fig. 27, where a cambered slender wing is shown at 1° angle of attack, we see a row of near-circular, small black patches behind the inner part of the wing; with increasing angle of attack, the row of patches disappears. Maltby, in Ref. 6, considers that these patches represent a row of streamwise vortices in the boundary layer that are caused by an instability of the 3D shear flow in the region of the cambered, swept leading edge. It has also been inferred by McDevitt and Mellenthin in Ref. 7 that these vortices exist on cones at high Mach number; some of their representative results are shown in Fig. 28. This figure illustrates an oil-film study on a 10° half-angle cone at 5° angle of attack with a transitional attached boundary layer immersed in a Mach 7.4 airstream. In the laminar region of the flow near the cone apex and on the windward side, the delicate pattern of the skin-friction lines has a distinctively different appearance and direction from that farther back on the leeside. This regular pattern of leeward streak lines (separation lines?) is thought to be indicative of the existence of streamwise vortices entrained within the boundary layer. Clearly, the presence of the vortices substantially alters the appearance and the direction of the local skin-friction line pattern reflecting the interaction between the vortices and the mean crossflow.

Another example is depicted in Fig. 29, where similar evidence of small-scale streamwise vortices immersed within the boundary layer on a hemisphere cylinder in transonic flow is shown. It is unclear, however, whether small-scale vortices of this type are the precursors to 3D separation, whether they are modifiers, whether their effect is relatively minor, or whether all or some of these conditions apply. In hypersonic flow, we might expect that these arrays of vortices could influence the heat transfer to the body — at high and low Mach numbers, the answer is that we do not understand the physical processes that are underway. This scenario is similar to the modelling question in turbulent flows, resembling also the phase transition phenomena in chemistry and physics. Advanced concepts are definitely required so that modelled equations average out the small-scale structures and, at the same time, give the correct bifurcation behavior at the appropriate critical Reynolds number(s).

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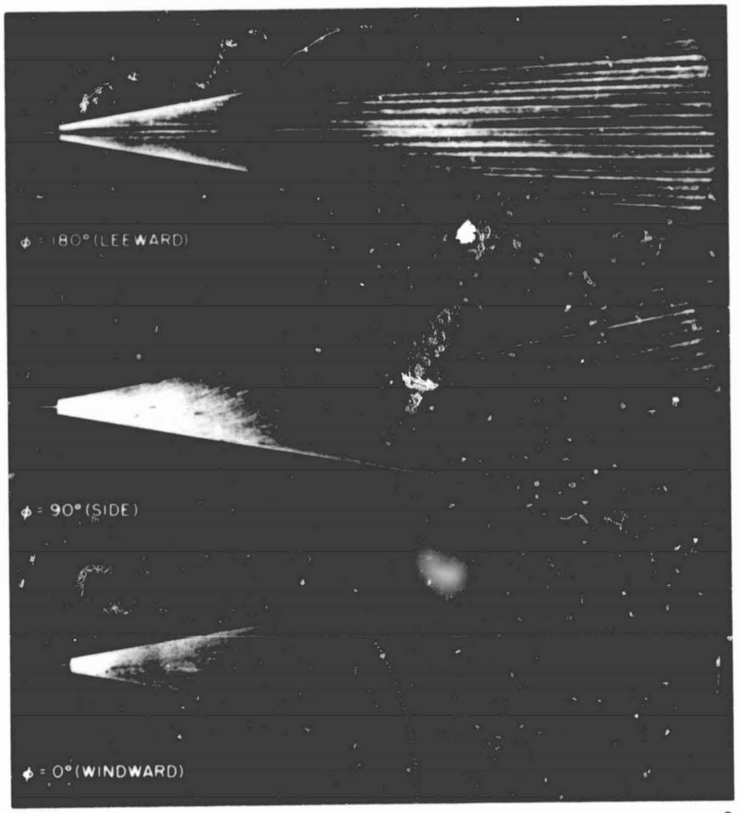
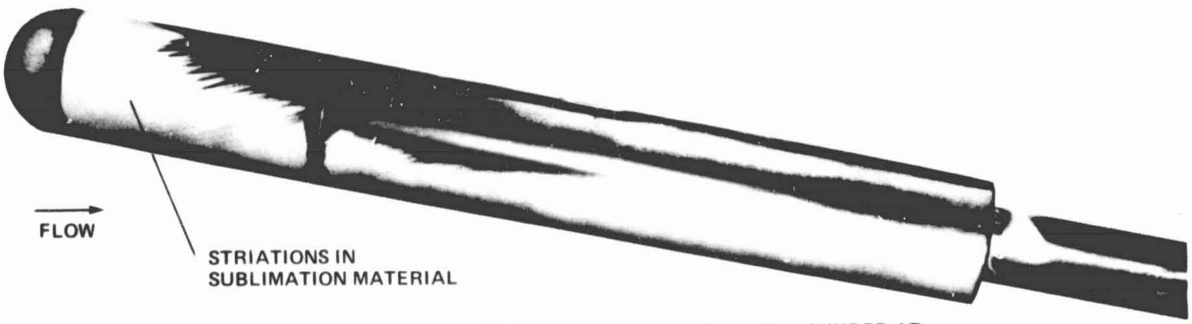
EVIDENCE OF VORTICAL STRUCTURES ON CONE AT ANGLE OF ATTACK



OIL-FILM STUDY ON A 10° SEMI-ANGLE CONE AT $\alpha = 5°$, $M_\infty = 7.4$, $R_{L_\infty} = 3 \times 10^6$, $T_T = 1050°K$, (McDEVITT AND MELLENTHIN 1969)

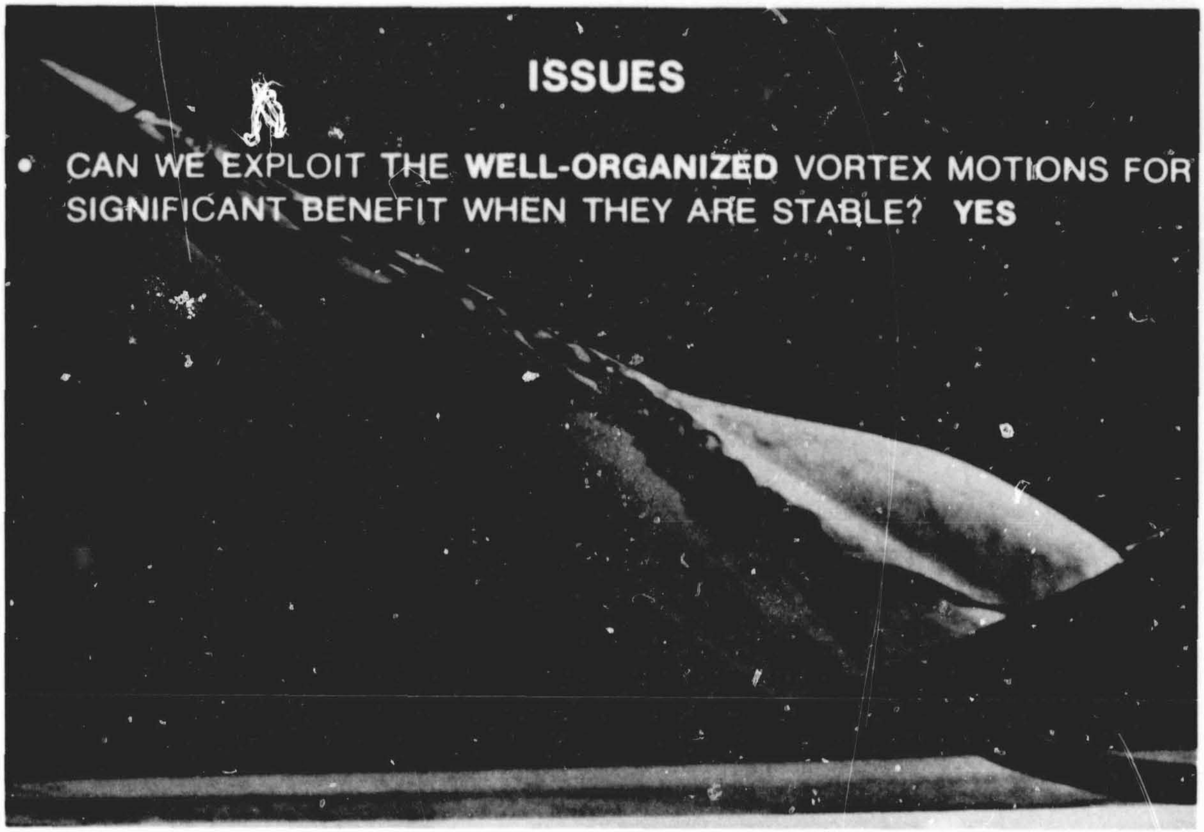
F28

EVIDENCE OF VORTICAL STRUCTURES ON HEMISPHERE-CYLINDER AT ANGLE OF ATTACK



SUBLIMATION MATERIAL ON HEMISPHERE-CYLINDER AT $\alpha = 19°$, $M_\infty = 1.2$, $R_{L_\infty} = 4.9 \times 10^6$, $L = 7.5\ D$, $D = 2.6$ in.

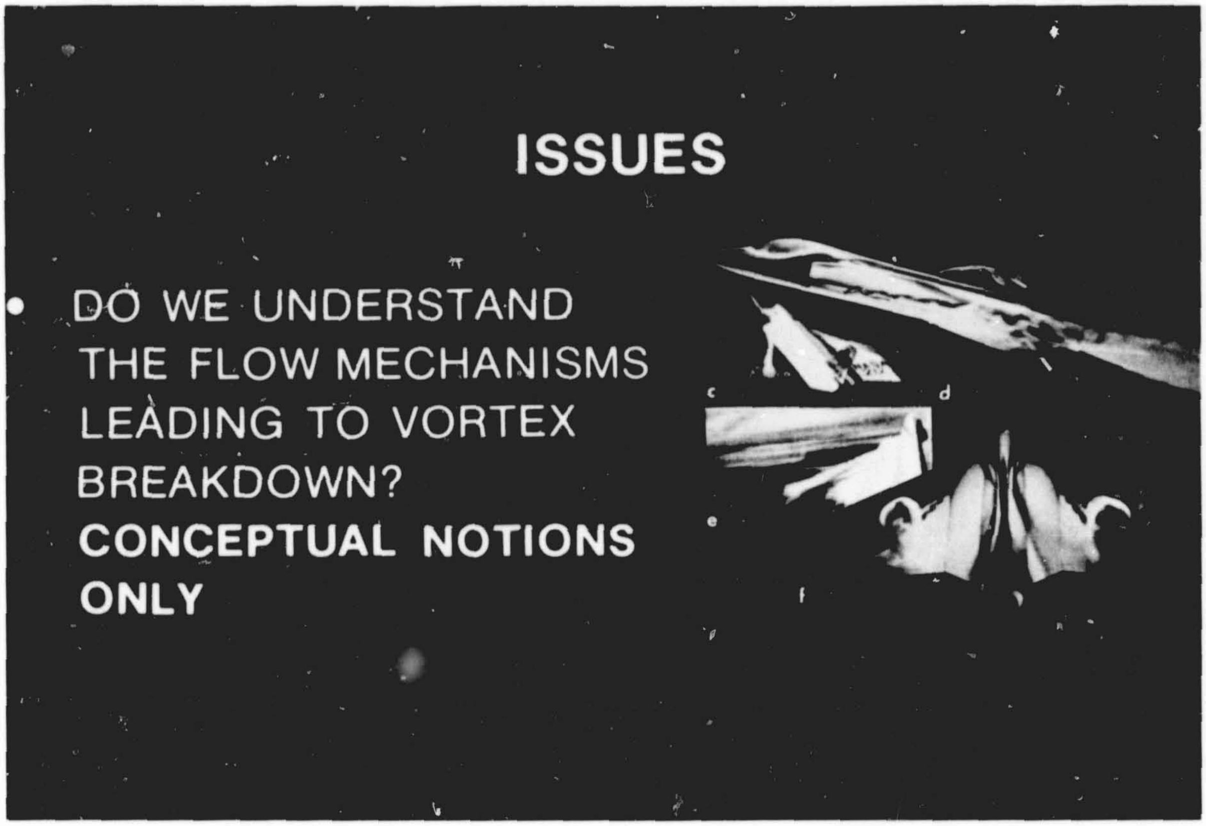
F29



F30

When a 3D boundary layer detaches from the surface it will, almost without exception, leave along a swept separation line, rolling up in the process into a well-organized nominally steady vortical motion. The underlying mechanism appears to be independent of both Reynolds number and Mach number, although under laminar conditions the flow features are normally more exaggerated. Hence, the overall details of many flows of practical interest can be determined in a water-tunnel facility, in which aircraft and missile designers can make changes to configurations quickly and cheaply.

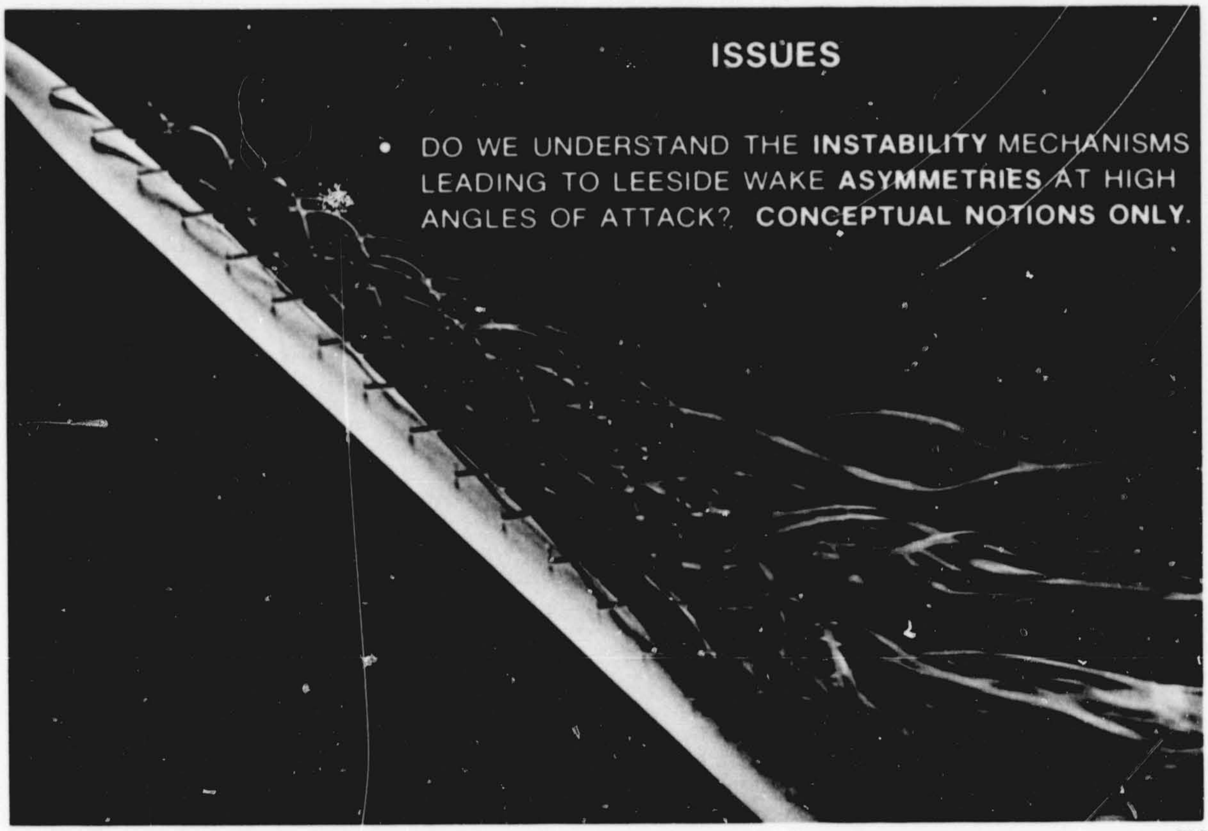
It is clear that when the leeside 3D separated flow fields are symmetric and stable, whether from the forebody or from other sharply swept edges farther downstream, the suction pressures induced by the coiling vortex motions can add substantial nonlinear components to the normal force as angle of attack is increased.



F31

The enhancement to the lift on a body provided by leeside streaming vortical motions is eventually limited when breakdown of the vortices occurs over the body. Currently, there is no theory available to predict the effect of vortex breakdown on the lift of an aerodynamic configuration. According to Wedemeyer (Ref. 8), explanations for vortex breakdown can essentially be divided into two categories: those that relate breakdown to an instability mechanism and those that do not. The two forms of vortex breakdown, called the bubble (axisymmetric) form and the spiral form, are frequently assumed to be different phenomena, although the bubble form is rarely found about a moving aircraft. Based on experimental observations, the bubble form appears to be the result of a change in topology only rather than related to a flow instability; to the contrary, the spiral form of breakdown is considered to be initiated by an instability resulting from an amplification of spiral perturbations.

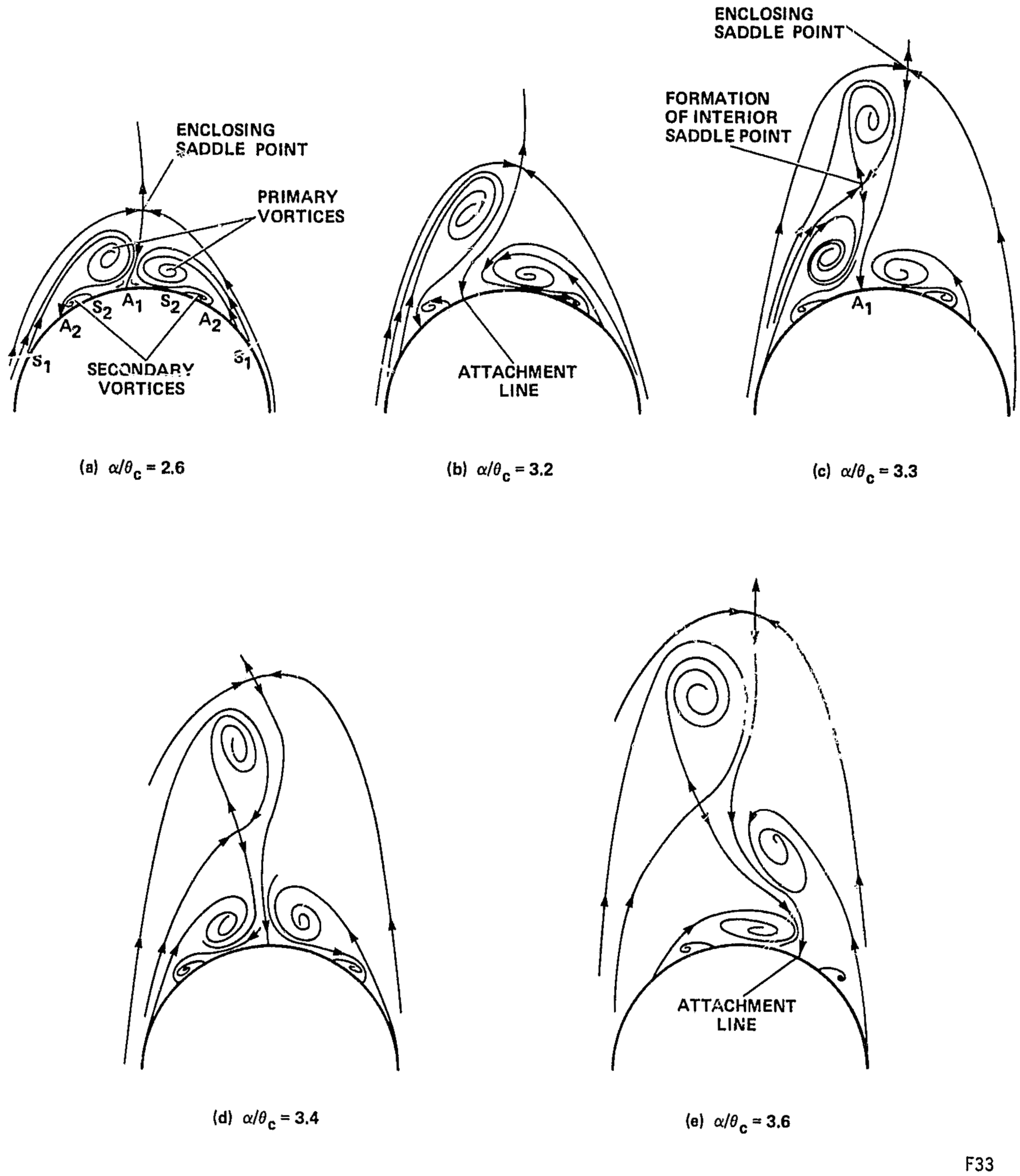
All theories predict vortex breakdown to occur within the experimentally observed range of swirl angles and the sensitivity of breakdown to the severity of axial pressure gradients. No theory, however, yields the flow detail in the breakdown zone, nor an accurate location of breakdown to compare with experimental results.



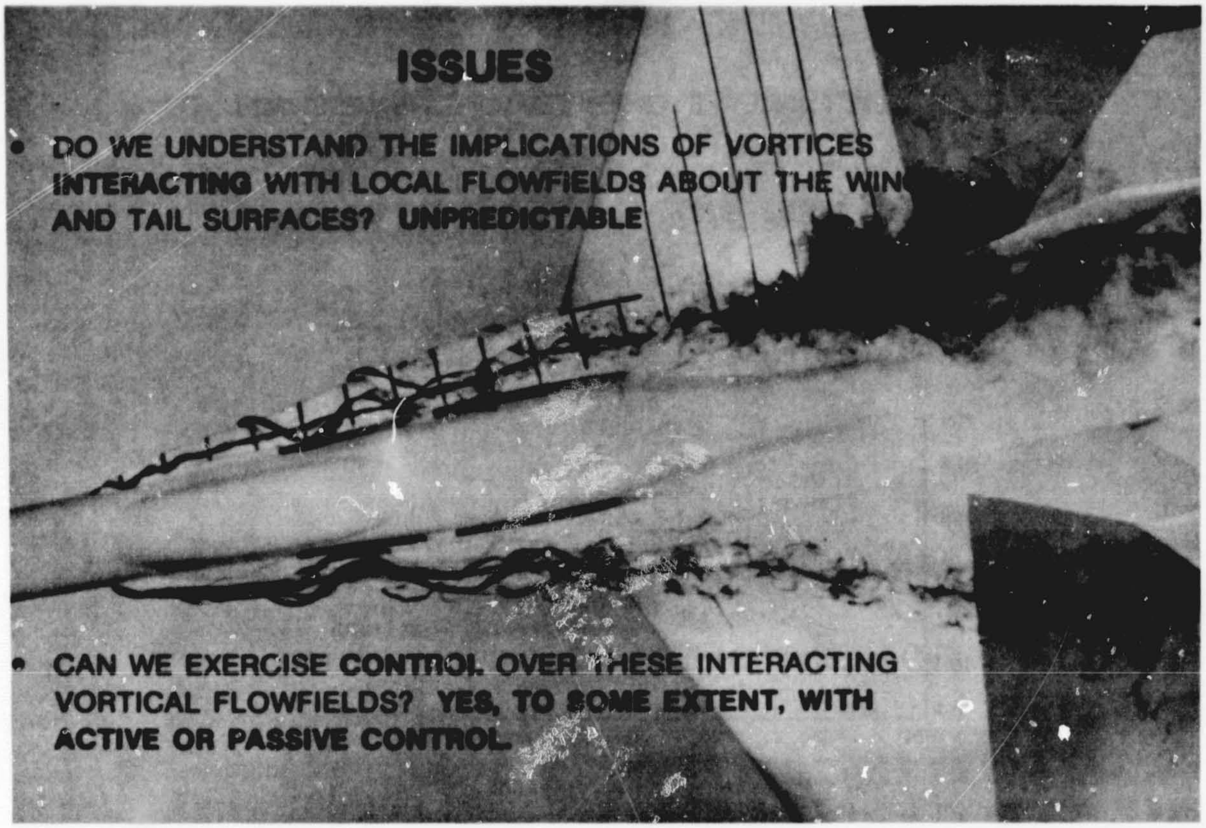
F32

Hypotheses have been advanced to explain the phenomenon based on the use of the impulsive flow analogy and the stability of the flow past a 2D circular cylinder. Details of the assumptions in these hypotheses are explained in Ref. 9. A typical flow topology in cross-section is depicted on Fig. 33, illustrating the conceptual side-to-side structural development of the subsonic flow about a slender forebody of nose semi-apex angle, θ_C.

Let us assume an asymmetric disturbance to originate at the nose, of the same rotation, say, as the port side primary vortex. If this disturbance amplifies in the vicinity of the enclosing saddle point as a consequence of instability of the inflexional velocity profiles, there will be an effective increase in the vorticity of the port-side primary vortex. This vortex will enlarge slightly and move away from the surface as shown in Fig. 33(a). As the relative incidence increases up to 3.2, the feeding shear layer continues to stretch, as shown in Fig. 33(b). At a relative incidence of 3.3, in conjunction with the appearance of gross unsteadiness of the secondary vortices, the elongated shear layer itself passes through a shedding stage, as shown in Fig. 33(c), until at a relative incidence of 3.4 there is definitive evidence of a third spiral vortex motion, as shown in Fig. 33(d). In order that the two vortices of the same rotational direction be able to coexist in tandem on the left-hand side, the rules of topology (Ref. 10) instruct us that a new saddle point must be inserted between them, as shown in Fig. 33(c). As the relative incidence increases still further, the starboard-side primary vortex begins to grow, as shown in Fig. 33(d) and (e), resulting eventually in the repetition of the shedding process for the opposite side; these incidences at which shedding occurs correspond with the maximum induced side loads. Note that the one crossflow streamline emanating from the enclosing saddle point to the body at A1 as shown, for example, in Fig. 33(e), always partitions the left- and right-hand sides of the wake. Except during the shedding process, each flow field is composed of well-organized spiral vortex motions.



CONCEPTUAL DEVELOPMENT OF ASYMMETRIC LEESIDE VORTEX WAKE STRUCTURE



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The leading-edge extension, or LEX as it is commonly called, offers the advantage that induced lift, provided by the vortices from the sharply swept edges, can be used beneficially to extend combat-maneuvering capabilities. These benefits can include an elevation in maximum lift that is now available at a higher angle of attack, an improved steadiness in rolling-moment performance, and lower root-mean-square wing-root bending moments, as representative examples. It also appears that in transonic flow, the vortex from the LEX avoids the necessity for the formation of the usual forward branch of the wing shock pattern by providing a "soft" boundary for the flow turning inboard over the leading edge, instead of the "stiff" boundary given by the fuselage side. A substantial discussion by Skow and Erickson on modern fighter-aircraft design for high-angle-of-attack maneuvering is available in Ref. 11.

At low angles of attack, the vortex emanating from a LEX will pass over the wing close to the surface, and farther downstream it will be adjacent to both horizontal and vertical tail surfaces. Wing-flap deflection will, of course, cause a significant downwash to be exerted on the vortex and readjust the position of the vortex relative to the tail. Moreover, the pressure field imposed by the tail may promote vortex breakdown; this may be a significant problem under sideslip conditions. The overall outcome is that both lift characteristics and longitudinal stability can be affected by vortex interaction with the tail surfaces.

At high angles of attack, the horizontal tails have less effect on vortex behavior due to the dominance of the wing pressure field. Several of our current fighter aircraft feature twin vertical-tail arrangements to maintain directional stability in the extended angle-of-attack range attainable with wings that include leading-edge extensions. Improper placement of the vertical tails can promote premature vortex breakdown and thereby limit the maximum lift obtainable, influencing both the longitudinal- and lateral-directional stability levels.

The sharp edge of the LEX fixes the 3D separation line there so that there is controlled flow separation about this component. Tailoring the camber and the sweepback of the LEX will clearly influence the position of the ensuing vortex. Small strakes on the forebody can be beneficial to forcing symmetric vortices to exist at higher angles of attack, but may cause strong effects on the lateral stability. Usually, it is preferable to reshape the cross-section of the forebody into a shark-like snout (see Ref. 11). Control of the orientation of forebody vortices can be implemented by tiny amounts of normal or tangential blowing, emerging into the flow from one orifice asymmetrically disposed with respect to the leeward meridian and initially beneath the vortex that grows rapidly away from the surface. This technique has the ability not only to return the asymmetric flow to a near-symmetric one as the blowing momentum increases but is powerful enough to produce a further movement of the forebody vortices to provide sideforce in the opposite sense to that given by the initial asymmetry. Asymmetric blowing can hence be used as a means of direct sideforce control to prevent departure of a fighter into a spin condition.

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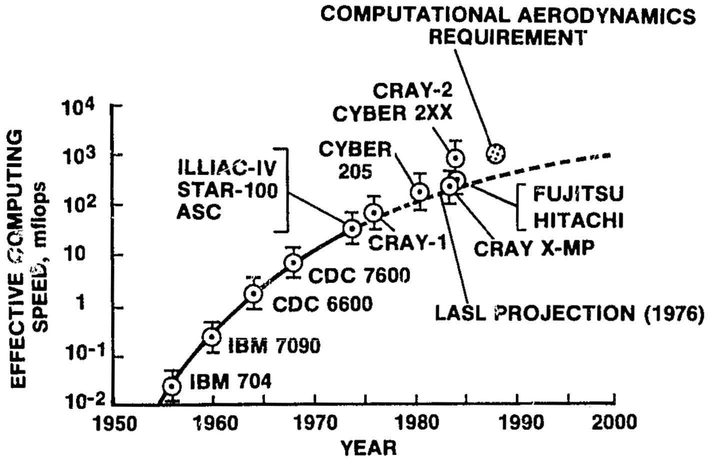
ISSUES

- CAN WE USE THE NAVIER-STOKES EQUATIONS, ASSUMED TO GOVERN FLUID MOTION, TO **COMPUTE** VORTICAL FLOWS ABOUT COMPLEX AERODYNAMIC CONFIGURATIONS AT HIGH ANGLES OF ATTACK? **NOT YET; INSUFFICIENT COMPUTING POWER**



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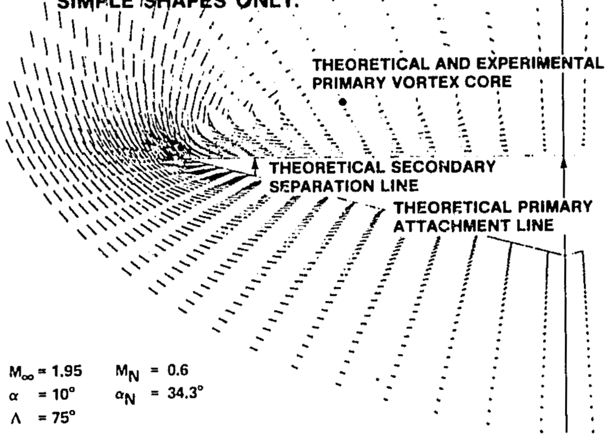
ISSUES

- WITH APPROPRIATE SIMPLIFICATIONS OF THE NAVIER-STOKES EQUATIONS, AND WITH OUR **CURRENT** UNDERSTANDING OF MODELLING TURBULENCE, ARE WE ABLE TO COMPUTE VORTICAL FLOWS ABOUT CHOSEN **AERO-DYNAMIC** COMPONENTS? **YES, BUT FOR SIMPLE SHAPES ONLY.**



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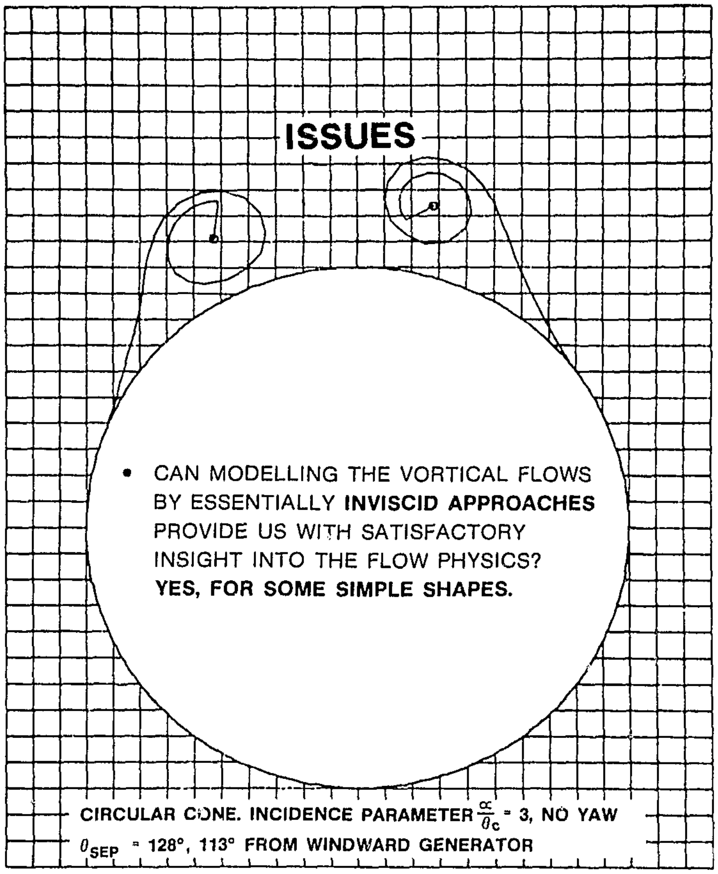
At least one additional order of magnitude in effective computing speed is required for us to be able to come near to analyzing numerically the entire flow about a real aerodynamic vehicle. Nevertheless, some intriguing and impressive results are being and have been obtained from computations of laminar flow fields about simple 3D aerodynamic components using approximate forms of the Navier-Stokes equations (see the review in Ref. 10). Moreover, the potential exists for obtaining satisfactory answers in turbulent flow once appropriate turbulence models can be found. Unfortunately, even these simple shapes must be surrounded with relatively coarse computational meshes; otherwise, the available computer storage on our largest machines becomes saturated. With our present capabilities, we arrive at an impasse. On the one hand, the singular points in the flow and on the body surface usually have simple, fundamental forms and their types, number, and placement, practically characterize a real separated flow. On the other hand, it is just in the vicinity of these singular points that a finite-difference scheme requires inordinately fine mesh spacing to capture their behavior. Even supposing that sufficient computer storage were available for the mesh to be tightened, computation costs would be increased, perhaps to an unacceptable degree. As a way out, we suggest that it may be possible to make a useful advance in the computation of 3D separated flows if finite-difference methods could be combined with a separate treatment (perhaps involving analytic or finite-element methods) of the singular points, thereby obtaining an adequate resolution in the vicinity of the singular points and avoiding very fine meshes.



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On wings with sharply swept leading edges, 3D separation occurs at the salient edges, being virtually independent of the oncoming boundary-layer properties at the high Reynolds numbers of interest to us. In the limit of infinite Reynolds number – or, for practical purposes, at high enough Reynolds numbers – the coiled viscous shear layer may be modeled approximately by an inviscid-flow vortex sheet. In other words, we adopt a viewpoint similar to that underlying the use of the Kutta-Joukowsky condition for determining flow at the trailing edge in inviscid wing theory. We say that viscosity causes the separation; the location is determined by the edge geometry, after which the flow may be modelled as an inviscid flow. The local behavior of a vortex sheet as it leaves the vicinity of a salient edge is tangential to either the top or underside of the edge, depending on the sign of the shed vorticity and on whether the external mean flow is directed inboard or outboard. In the region of the vortex external to the core, the axial velocity does not change substantially, and we may describe it to a satisfactory degree of approximation by ignoring diffusion (i.e., viscous) effects there. Diffusion is only important in the inner part of the vortex core where there are substantial velocity gradients. For a 3D core growing in space, the swirling fluid is drawn into the core, acquiring a high axial velocity as it escapes along the axis. Reynolds number does not appear to have a significant effect on the development of the large-scale structure of the flow, whereas the core center diminishes as Reynolds number increases. In numerical calculations of incompressible flows about swept edges there seems to be a qualified but free choice available as to whether the vortex sheet should be represented as collections of isolated vortices, as line vortices, or as a continuous sheet. Particular mathematical or numerical difficulties in the stability of the roll-up process have been overcome.

On bodies, the separation location is unknown a priori. We must attempt to calculate its position by 3D boundary-layer theory, which requires an appropriate external flow, or map its position from experimental surface oil-flow visualization. In the former, an iteration between the boundary layer and inviscid flow is required, with a guessed separation-line position, followed by subsequent correction of the inviscid pressure distribution. Once the separation line is supplied, an inviscid vortex sheet model of the separated flow can be invoked (in incompressible flow at least) on which the following boundary conditions will be adequate to determine it completely. The sheet must leave the surface tangentially along the separation line. It is an open vortex sheet in the sense that fluid at the same total pressure wets the vortex sheet on either side. Both pressure and velocity are continuous across the sheet, which is a stream surface. The velocity on the upstream side of the sheet provides the convective component to remove the vorticity from the surface.

On the downstream side of the sheet, replacing the Kutta condition for separation at a sharp edge is the requirement that the velocity be directed downstream tangentially to the separation line. On the upstream side of the separation line, the surface streamlines of the inviscid model are inclined to the separation line but are, of course, still tangential to the wall. The vortex sheet model may be used on simple shapes, such as pointed right-circular and elliptic cones, for which the separation lines are along generators and the coordinate geometry presents few difficulties. On more complex configurations the solution eludes us, for boundary-layer calculations have not usually been successful in providing separation-line positions, particularly when separation starts some distance back from the nose. Moreover, we still do not have a suitable flow model for the breakaway dividing surface, under conditions where neither conical nor slender body flows exist.

There has been some recent success in numerically solving the Euler equations in which vortex flows around wings of high sweepback angle have been simulated. It appears that if the computed results are to be realistic, the edge must be relatively sharp to ensure that the development of the "shear layer" is virtually insensitive to Reynolds number. This is the only possible way to represent a separated flow field by the Euler equations in which there is artificial viscosity in the numerical scheme.

CONCLUDING REMARKS

A study of the issues involved in the understanding of complex vortical flows leads us to the following remarks:

- We have an unambiguous definition of separation in three dimensions if a separation line is construed to emanate always from a saddle point even in cases where the origin is obscured by lack of resolution.
- The structure and mechanism of separation and the ensuing coiled-up vortical motions are understood in mean-flow terms.
- We are unable at this time to formulate a principle that will distinguish between the scale of vital and unimportant organized vortical structures.
- We are able to exploit the well-organized vortex motions for significant benefit when they are stable.
- We have only conceptual notions to understand the instability mechanisms leading to vortex breakdown and leeside wake asymmetries at high angles of attack.
- We are unable to predict the implications of vortices interacting with local flow fields about the wing and tail surfaces, although we can exercise control over these interacting flow fields to some extent with active or passive control.
- With appropriate simplifications of the Navier-Stokes equations, and with our current understanding of turbulence modelling, we are able to compute vortical flows about chosen aerodynamic components at high Reynolds numbers, but only for very simple shapes.
- Modelling of vortical flows by essentially inviscid approaches can provide us with insight into the flow physics, but our understanding extends only to simple shapes.

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ACKNOWLEDGEMENTS

Frontispiece	Ames-Dryden
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F3	Ames-Dryden
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