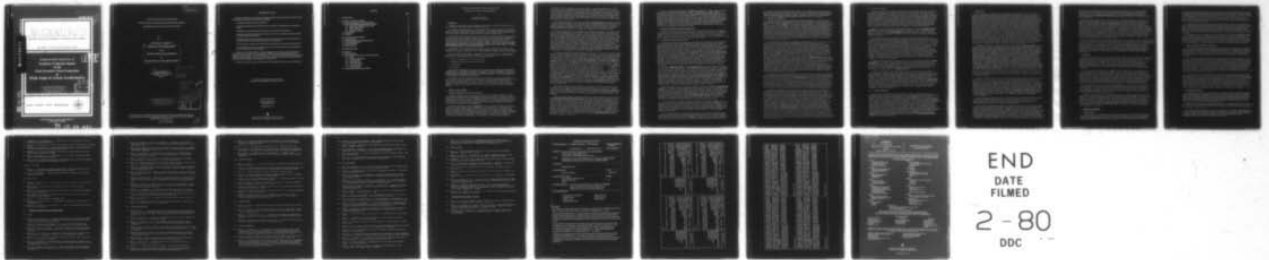
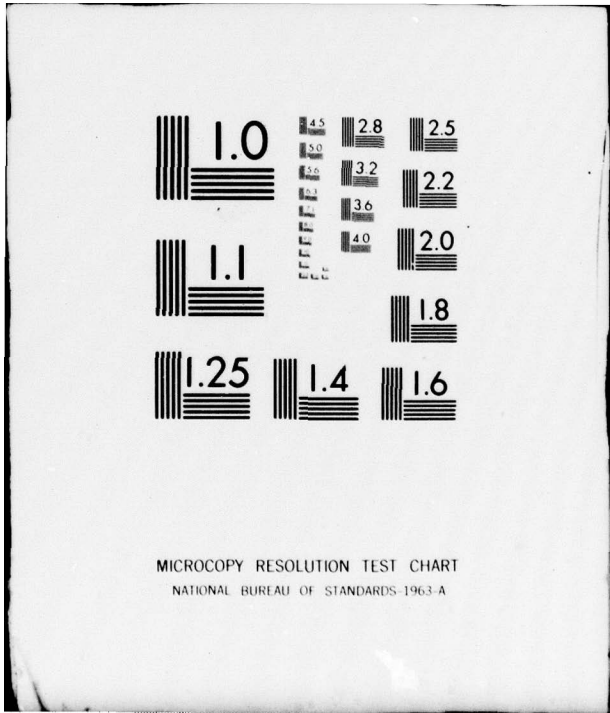


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AGARD ADVISORY REPORT No. 145

Technical Evaluation Report  
on the

Fluid Dynamics Panel Symposium

on

High Angle of Attack Aerodynamics

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AGARD Advisory Report No. 145  
6 TECHNICAL EVALUATION REPORT  
on the  
FLUID DYNAMICS PANEL SYMPOSIUM  
on  
HIGH ANGLE OF ATTACK AERODYNAMICS

by  
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The Proceedings of the AGARD Fluid Dynamics Panel Symposium on High Angle of Attack Aerodynamics, which was held in Sandefjord, Norway on 4-6 October 1978, are published as AGARD CP 247, January 1979.

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TECHNICAL EVALUATION REPORT ON THE FLUID DYNAMICS PANEL

SYMPOSIUM ON HIGH ANGLE OF ATTACK AERODYNAMICS

BY

Edward C. Polhamus  
NASA/Langley Research Center

1. INTRODUCTION

A symposium on High Angle-of-Attack Aerodynamics, organized by the AGARD Fluid Dynamics Panel, was held at Sandefjord, Norway from October 4 through October 6, 1978.

The stated aim of the Symposium was "to bring together those working on fundamental fluid mechanics aspects of flight at high incidence and those concerned with the aerodynamic design of flight vehicles, to review developments in design and analysis techniques and to study the implications of available experimental data and theoretical results, including those concerned with asymmetric flight."

The symposium was very timely in view of the current interest in providing both military aircraft and missiles with high levels of maneuver capability. The subject of high angle-of-attack aerodynamics is pertinent not only from the standpoint of understanding and predicting the aerodynamic effects of the complicated separated flows encountered during high angle-of-attack excursions as they pertain to piloting and performance problems but from the important standpoint of developing the technology required to fully exploit the advantages of "controlled separation" concept. This concept is based on the highly stable leading-edge vortex flow with its well known vortex induced lift and a large number of the papers dealt with various aspects of this technology development.

The symposium was well organized, and well received by an active audience of 145 people. The symposium owed its success to the efforts of the Program Committee, the Panel Executive and the Meeting Coordinator (see section 4) and, of course, to the time and effort of the authors who were all well prepared.

A total of thirty-two formal papers, organized into four topical sessions, were presented with an additional seven informal short papers being presented in an open workshop session. The symposium was concluded with a round table discussion. The four topical sessions were:

I - Studies of Configurations of Practical Application

II - Mathematical Modeling and Supporting Investigations

III - Design Methods

IV - Air Intakes

The thirty-two formal papers and seven open session papers have been published as AGARD Conference Proceedings No. 247. The purpose of this paper is to provide an overview and evaluation of each of the topical sessions, and conclusions with regard to the impact on the state of technology, including some thoughts relative to areas where increased effort would appear profitable. The open session papers will be discussed under the appropriate topical session.

The symposium papers are listed as references and are identified in the text by authors and the reference number. For the convenience of the reader a list of recently published papers relative to high angle of attack aerodynamics which were cited in the various symposium papers has been added to the reference list under various subject headings. Because of the large number of papers cited, those published prior to 1976 have not been included and the reader is referred to the individual symposium papers for listings of earlier papers. Finally, a list of additional references cited in this paper is included.

2. OVERVIEW OF TOPICAL SESSIONS

2.1 Studies of Configurations of Practical Application

The papers selected for the first session dealt primarily with high angle-of-attack aerodynamic characteristics encountered during the development phase of specific aircraft configurations or during applied research studies of complete configurations using models of existing or conceptual aircraft. As a result this session was very effective in emphasizing the "real life" aspects of high angle-of-attack aerodynamics, in describing new concepts, and in setting the stage for the subsequent sessions which, in general, tended to deal with the more fundamental fluid dynamics research and mathematical modeling studies related to high angle of attack aerodynamics.

The session began with a paper by Orlik-Ruckemann<sup>1</sup> in which he reviewed the effects of flight at high angle of attack on dynamic stability parameters and their significance in the analysis of aircraft motions. The review was based primarily on the material presented during the Fluid Dynamics Panel Symposium on Dynamic Stability Parameters held in the spring of 1978. Examples of the rather severe non-linear variations of the various damping derivatives and cross derivatives with angle of attack (which often occur in the moderate to high angle-of-attack range) were shown and the lack of adequate methods of estimating the derivatives was emphasized. The strong effects of vortex flows on the dynamic derivatives were discussed and the importance of configuration in controlling these effects were

illustrated by the use of forebody nose shaping in relation to vortex flows generated by the viscous cross flow in the nose region and by the use of wing strakes to generate vortex flows over the wing which resulted in large reductions of the nonlinear effects. While many subjects, such as the inclusion of angle of attack non-linearities, time-dependent effects and aerodynamic cross-coupling in aircraft motion studies were discussed the implications that more research into the basic fluid dynamic aspects of dynamic stability characteristics (including the effects of Reynolds number and Mach number) at high angle of attack is needed and that improved aerodynamic theories should be developed are probably the most pertinent ones in the context of the current symposium. Other papers touching on dynamic stability derivatives will be discussed later.

Introducing the main portion of session I was a paper by John and Kraus<sup>2</sup> which reviewed the current interest in a vastly expanded altitude - Mach number envelope and raised maneuver boundaries as it relates to fighter aircraft effectiveness. They reviewed the basic aerodynamic characteristics of different fighter configurations in separated flow regions, concepts for artificial stabilization and the need for auxiliary momentum generating systems for control in portions of the flight envelope. The paper provided an excellent introduction to this session on configurations of practical application.

When one considers the subject of "configurations of practical application", in the context of high angle of attack aerodynamics, it is only natural to think in terms of configurations which apply some version of the "controlled separation" concept. It was not surprising therefore to find that a large majority of the papers presented in session I dealt with configurations which utilized, as part of their basic design, features which promote the highly stable separation induced vortex flow which, in the words of one of the speakers, "creates order out of havoc". The orderliness of this type of separated flow over a wide angle of attack range and the large vortex lift contributions that it can provide have made it the subject of extensive research and development for several decades and a growing number of aircraft owe their basic designs to this phenomena. Probably the most classic example of the application of the controlled separation concept is the Concorde supersonic transport and some high angle of attack characteristics of the Concorde from both wind tunnel and flight were described by Collard.<sup>10</sup> While the results indicated that the large benefits of vortex flow on the lift characteristics were obtained, some deterioration in stability and control in the high angle of attack range (associated with the secondary vortex flow and the inboard movement of the primary vortex) was observed thereby emphasizing the need for accurate methods of including these flow details in the aerodynamic theories.

With regard to maneuvering aircraft the application of the vortex lift concept in the form of slender maneuver lift strakes combined with moderately swept main wing panels is receiving considerable attention and this interest was emphasized by the fact that seven of the eleven papers in the session were devoted, at least in part, to vortex lift strake configurations. These strakes, which provide high levels of lift for maneuvering for a relatively low structural weight and low gust response, are basic design features of several fighter aircraft. The papers by Moss<sup>4</sup>, Smith and Anderson<sup>5</sup>, and Bucciantini, Silvestro and Fornasier<sup>40</sup> described some experiences with strake-wing configurations gleaned from the development of various specific aircraft. They emphasized not only the general benefits of the concept but the detailed tailoring, associated with the complicated vortex interactions, required in the wind tunnel to assure satisfactory flying qualities at high angles of attack. Of particular interest was the data presented by Moss<sup>4</sup> on the various dynamic stability derivatives, buffet response, and wing rock which was obtained over a relatively large angle of attack range and at high subsonic Mach numbers. Benefits of vortex lift strakes were illustrated for all of the above parameters but of possibly equal significance is the fact that the dynamic derivatives were studied in the Mach range pertinent to the high subsonic speed maneuvers of interest to modern fighter aircraft. The need for continued parametric experimental studies to provide design guidance and an improved understanding with regard to flow modeling was clearly emphasized by the above papers. In this regard, during the aerodynamic development of the F-16 a large amount of experimental data on the characteristics of nose strakes and wing strakes was obtained and an analysis presented by Smith and Anderson<sup>5</sup> took the form of correlation parameters describing the control of the pitching moment characteristics and the prediction of the lift and drag increments. Regarding the need for further well-structured parametric studies the review paper by Lamar and Luckring<sup>24</sup> presented in the design methods session described a recent extensive parametric study of strake-wing design parameters utilizing separate strake and wing force balances and surface flow visualization to establish the vortex flow interactions.

Another dynamic stability subject encountered with configurations of practical application and one that generally is not considered early enough in the design phase is that of the effect of external stores and the paper by Booker<sup>3</sup> reviewed some effects of store inertias and aerodynamics on high angle of attack lateral-directional characteristics. This study which illustrated the fact that the addition of the stores often cause a deterioration of the stability and an increase in the non-linear angle-of-attack dependence of the damping derivatives calls attention to the need for wind tunnel studies early in the design phase.

A joint international study of a fighter type configuration during and beyond the stall was presented by Staudaehner, Laschika, Poisson-Quinton and Ledy.<sup>8</sup> The study included strakes, canards and various control surfaces. Of particular interest is an innovative extension to the current applications of the "controlled separation" concept consisting of the combination of the spanwise blowing concept and the vortex lift strake. In this research the vortex lift enhancement and control power provided by spanwise blowing, which has received considerable attention with regard to improving the vortex lift capability of wings of modest sweep, has been applied to the highly swept strakes of strake-wing combinations. Increases in lift associated with strake blowing were observed over the angle of attack range up to 80° with the increase in the region of maximum lift being equivalent (for  $C_{\mu} = 0.1$ ) to the basic strake increment and corresponding to a lift augmentation factor of approximately four. Improvements in the drag polar, longitudinal stability and buffet characteristics were also observed. Spanwise blowing also shows promise as a means for spin avoidance and spin recovery and Cornish and Jenkins<sup>9</sup> described wind tunnel tests of a model of the F-4 mounted on a spin rig in which spanwise blowing was particularly successful in arresting a steep spin.

The papers by Skow, Titiriga and Moore<sup>6</sup> and Bornemann and Surber<sup>11</sup> were summary type papers dealing with vortex flow interactions on two classes of vehicles. The first paper related to fighter configurations characterized by relatively long slender fuselage forebodies and their hybrid wings of the wing-strake type and the second described the characteristics of the space shuttle which has a large diameter, blunt fuselage and a relatively thick hybrid wing. In the fighter study emphasis was on the strong roles that vortical flow from the forebodies and hybrid wings and their interactions can play in defining the high angle-of-attack handling qualities and the departure and spin resistance characteristics. The shuttle study emphasized, among other things, the strong viscous flow effects associated with large forebodies of non-circular cross section and the wing leading edge vortex development and breakdown characteristics. Both papers illustrated the extensive wind tunnel testing required during the development of a vehicle and the need for improved understanding and mathematical modeling of viscous flows for arbitrary geometries at high angle of attack.

## 2.2 Mathematical Modelling and Supporting Investigations

This session dealt with mathematical modelling of the separation induced vortex flows encountered at high angles of attack and wind tunnel studies designed to establish (1) the details of the complicated flow patterns around slender wings and bodies of revolution at high angles of attack, (2) the various component interactions, and (3) the associated force and moment characteristics. The experimental studies, which are of considerable aid in the development and evaluation of improved mathematical modeling, covered a wide range of Mach number, angle of attack and Reynolds number.

### 2.2.1 Mathematical Modeling for Slender Wings

For thin wings with highly swept leading edges the highly stable leading-edge vortex system, fed by a vortex sheet connected to the sharp leading edge, can be reasonably well modeled by inviscid concepts. Until recently the major effort has been directed towards various slender-body approaches to the mathematical modeling. Because of their relative simplicity the slender-body approaches have been applied for a wide variety of camber and thickness distributions and for various wing motions and a great deal of insight into vortex flows has resulted. There are, of course, some serious limitations associated with slender-body theory since it (1) does not allow for a Kutta condition at the trailing edge, which is a serious restriction at subsonic speeds, and (2) does not account for the reduced vortex feeding rate at supersonic speeds as the Mach cone approaches the leading edge. As a result of these practical problems and the rapidly increasing computer capability the emphasis on mathematical modeling is shifting to the various fully three-dimensional approaches. This trend was emphasized during the symposium (see also reference 12<sup>4</sup>) in that nearly all of the wing modeling for vortex flow was based on non-slender wing approaches. Some of the theoretical modeling work was described in papers dealing with design methods in session III but will be briefly described here for completeness. The fully three-dimensional mathematical models to be discussed here are divided into two general approaches, the free vortex sheet model and the multivortex model. Other theoretical approaches which, while providing useful results, do not provide the potential of predicting the details of the complete flow field are discussed in section 2.3.

The papers by Lamar and Luckring<sup>24</sup> and Tinoco and Yoshihara<sup>26</sup> described and evaluated the subsonic free vortex sheet method being developed in the Boeing/NASA Leading Edge Vortex Program. In this method the wing is paneled with biquadratically varying doublet panels and bilinearly varying source panels with zero mass flux boundary conditions imposed on the wing surface and the Kutta condition satisfied at all edges. The free vortex sheets are paneled with biquadratically varying doublet panels with zero mass flux imposed on the sheet along with the constraint that it be locally force free. The free sheet is a simplified model of the physical vortex core region. The wake shape was frozen and the no pressure jump boundary condition satisfied by either first or second order pressure formulations. The evaluation presented in the two papers indicate that the method provides an accurate modeling of the strong trailing edge effects that seriously limit slender-body methods and that it predicts with good accuracy the overall forces and moments for slender pointed wings for angles of attack below vortex breakdown. The predicted surface pressure distributions are in good agreement with experiment for both flat and cambered wings in both straight and yawed conditions except in regions where the secondary vortex has noticeable effects. The method is being refined and extended to arbitrary planforms.

A promising extension of the free vortex sheet method was described in the paper by Hoeijmakers and Bennekers<sup>25</sup>. This method follows the same general formulation as the method described above but provides a scheme for the inclusion of the entrainment effect of the rotational cores and utilizes different numerical approaches and iterative procedures which appear to have the potential of providing reductions in computer time. The paper presented preliminary results illustrating some effects of various assumed levels of the entrainment parameter. An experimental study related to the entrainment parameter was briefly reviewed in the open workshop session by Verhaagen and Vander Snoek<sup>39</sup>. From detailed flow measurements in the vortex field of an aspect ratio 1.0 delta wing at 20° angle of attack the free shear layer and rotational core were established and the circulation and axial mass flow of the core cross-section was determined from which estimates of the entrainment factor can be made.

A brief description of the application of a multivortex, or discrete-vortex, approach to the modeling of a slender wing and a slender canard-wing configuration was described by Kandil<sup>37</sup> in the open workshop session. In this method the continuous free vortex sheets are modeled by a distribution of segmented free-vortex lines and the bound sheet is modeled by a bound vortex lattice. Examples of the resulting vortex wake shapes for a steady state angle of attack case and a steady rolling case at zero angle of attack were presented and it was stated that while the calculated pressure distributions were generally less than satisfactory due to the discrete-vortex approximation the overall aerodynamic characteristics were good.

A very encouraging extension of the mathematical modeling of the flow about slender wings with separation induced flow is that associated with the unsteady calculation of vortex sheets emitted by highly loaded lifting surfaces carried out by Rehbach<sup>14</sup>. The method utilizes a point discretization of the vorticity field with the vortex vectors moving with the fluid and varying in time as a function of the local distortions of the velocity field. He applied the method to the time history of the vortex

core formation, vortex sheet instabilities, and the normal force development for slender rectangular and delta wings for impulsively started flow at high angles of attack. The similarity between the numerical results and water tunnel motion pictures is striking. The results regarding the time dependency of the normal force generally appear encouraging although a difference from the solution of Belotserkovskii (ref. 126) for the rectangular wing with leading edge separation is yet to be reconciled.

### 2.2.2 Slender Wing Flow Fields

As an aid to improved mathematical modeling a more complete knowledge of the flow about slender, sharp edge, delta wings with leading edge vortex flow has been established by surface flow studies, detailed surveys of static, dynamic and total pressures, and flow angularity in the near wake of a delta wing of  $A = 1$  in the paper by Hummel<sup>15</sup> for the turbulent boundary layer case. While in general the flow pattern was found to be quite similar to that deduced from previous studies, the relationships between the leading edge vortex, the secondary vortex and the trailing-edge vortex system are described in considerable detail. For the turbulent case studied the secondary vortex decayed rather rapidly and its remains were found rolling up into the trailing edge vortex. The combined secondary and trailing edge vortex system, which has a rotation opposite that of the leading edge vortex, moves downstream on a helical path around the leading edge vortex. The results of this study provides an excellent basis for the evaluation of theoretical flow field methods under development. In this connection it should be noted that the free vortex sheet theory discussed in papers 24 and 26 has recently (ref. 125) been used for a preliminary study of the counter rotating trailing-edge vortex system observed above. The calculated wake doublet strength distribution implies a trailing vortex roll up that is in qualitative agreement with Hummel's measurements.

In a study related to vortex breakdown Wedemeyer<sup>13</sup> investigated the stability of the outer parts of the core of the leading edge vortex. He related the leading edge sweep and angle of attack through Ludwig's stability criteria for helical flows to establish a leading edge vortex stability boundary as a function of aspect ratio and angle of attack for sharp edge delta wings. The angle of attack above which no stable vortex exists decreases with increasing aspect ratio (decreasing sweep angle) and in the low aspect ratio range is in good agreement with the experimental boundary for conditions where vortex breakdown has reached the trailing edge as established by other investigators. The study also illustrated the benefit of a wing strake in stabilizing the vortex flow on moderately swept wings and delaying the vortex breakdown that normally occurs early on this class of wing. One feature in the development of the stable vortex flow on the outer panel of wing strake configurations is the premature separation of the flow, induced by the strake, that leads to the outer panel vortex formation. In relation to this phenomena the paper by Fiddes and Smith<sup>1</sup> described their development of a simplified strake vortex model to investigate the influence of the strake induced flow. The vortices generated by the strakes were represented by a pair of infinite line vortices whose strength and location were selected by an analysis which combined attached flow lifting surface theory for the actual wing-strake combination and slender-body theory for the strake alone with vortex flow. Calculations using this model illustrated the increase in effective sweep angle due to the induced sidewash and the increase in the magnitude of the potential flow leading edge singularity due to the upwash, both of which would be expected to contribute to the observed premature leading edge separation on the main wing panel. An extension of this type of study to investigate the fundamental fluid dynamic aspects of the spanwise flow induced by the strake vortex in relation to the favorable influence in stabilizing the main panel vortex flow and the resulting benefits with regard to maneuver performance including reduced buffet would be very desirable.

In the supersonic speed range the leading edge vortex flow associated with slender delta wings with sharp leading edges maintains the general nature of the subsonic case until the leading edge approaches the sonic condition. The supersonic study by Szodrich and Ganzer<sup>21</sup> of the flow about a 73° delta wing covers a rather wide angle of attack and Mach range and explores the transition from leading edge vortex flow to flow with separation bubbles and shocks and finally to shock induced inboard separations. Their results in the vortex flow region indicate that for the wing studied the centerline shock appeared at about 16°, which corresponds to the condition where the two vortex sheets are in close proximity. Above a Mach number of about 3 the combined vortex flow and centerline shock was replaced by separation bubbles and twin shocks with the vortex type flow within the bubbles becoming detached at about 15°. Except for a brief reference to the supersonic application of the leading edge suction analogy in paper 24 no theoretical prediction methods for supersonic vortex flow were presented during the symposium.

As a result of experimental flow field studies such as those just described a reasonably good understanding of the high angle of attack flow about those slender wings which have their separation lines fixed by sharp edges has been developed and the experimental data is being used to improve theoretical modeling and to evaluate the accuracy of the resulting aerodynamic theories. While considerable progress has been made in theory development for the sharp edge case (except for the effects of secondary and tertiary vortices) little progress has been made in the evolution of theoretical methods for the prediction of the flow fields, and resulting forces and moments, for configurations for which the separation lines are not fixed at a sharp edge. For this type of flow viscous effects are important, not only with regard to the onset of separation induced vortex flow but with regard to its growth and structure. In contrast to the sharp leading edge case little progress has been made with regard to mathematical modeling of this type of vortex flow. However progress is being made in developing an improved understanding of this aspect of viscous flows through detailed experimental studies and the paper by Mirande, Schmitt and Werle<sup>12</sup> described a recent addition to this technology base. Their study involved low speed wind tunnel force tests and detailed flow measurements on a constant chord wing for a wide angle of attack range for sweep angles from 0° to 60° in 5° increments for a range of Reynolds numbers. In addition water tunnel flow visualization tests were conducted for some selected conditions. They demonstrated the effect of Reynolds number on the boundaries of the vortex flow domain for their rounded leading edge wing in the angle of attack and wing sweep plane for a Reynolds number range from  $0.8 \times 10^6$  to  $1.9 \times 10^6$ . The study provides a new and detailed flow study that should be useful in the modeling and evaluations required to develop a successful viscous flow theory. The important effects of Reynolds number on the illustrated vortex flow domain emphasizes the need for higher Reynolds number data.

### 2.2.3 Bodies of Revolution

Of particular importance with regard to aircraft stability and control at high angles of attack are the forces and moments generated on fuselage forebodies as a result of separation induced vortices for both symmetric and asymmetric flow conditions. In addition, the interference flows induced by these vortices in the region of the stabilizing surfaces can have a profound effect. The asymmetric separations on fuselage forebodies that occur at high angles of attack can result in aerodynamic moments which often dictate the aerodynamic control power required to assure vehicle controllability throughout the envelope of present-day maneuvering missiles and fighter aircraft. Because of the extreme sensitivity of these flows to geometry, viscous and compressibility effects and the lack of adequate theoretical methods the designer must rely on wind tunnel tests which, generally, are limited with regard to Reynolds number simulation. However, progress is being made with regard to theoretical modeling ranging from various types of inviscid modeling of the vortex sheets (where separation lines are determined from boundary layer calculations or empirical methods) to various solutions of the Navier-Stokes equations.

With regard to the various inviscid modeling approaches part of the paper by Spangler, Perkins and Mendenhall<sup>29</sup>, in Session III dealt with an incompressible application of a nose vortex shedding flow model. In the supersonic region McRae and Hussaini<sup>23</sup> have generated solutions of the Navier-Stokes equations, subject to a conical symmetry assumption, but which include viscous effects in the governing equations for sharp cones at angle of attack and have found the results very encouraging, especially for laminar flow conditions.

Three-dimensional turbulent flow modeling for arbitrary geometry and flight conditions, is not sufficiently developed for practical applications particularly for the high angle of attack condition and as in the case of slender wings detailed experimental studies are helpful in modeling and in evaluating theoretical results. In this regard Peake, Owen and Higuchi<sup>16</sup> described wind tunnel tests of a 5° semiangle circular cone in the Mach number range from 0.6 to 1.8 at angles of attack up to about 25°. In addition to the overall static forces and moments mean surface pressure measurements and laser velocimeter surveys of the fluctuating wake velocities were made and fluctuating surface pressures were measured at a Mach number of 0.6. The data obtained provides additional information, not only for the conditions corresponding to symmetrical flow patterns but with regard to the well known asymmetric flow patterns that develop on the lee side of slender bodies at high angles of attack and produce large out-of-plane forces and moments. In connection with the large out-of-plane side force and yawing moment developed at high angles of attack several of the symposium authors referred to a recent study by Rao (reference 50) in which he demonstrated the effectiveness of helical separation trips in preventing vortex-wake asymmetry. Rao's approach, which is an extension of a concept used for vortex-wake suppression on cylinders in a cross flow, disrupts the vorticity feeding mechanism at high angles of attack such that the primary vortex pair cannot be sustained.

Providing additional information at supersonic speeds is the very detailed investigation by Bannink and Nebbeling<sup>22</sup> of the surface flow and external flow field for a 7.5° semi-apex circular cone at a Mach number of 2.95 for angles of attack up to 34°. Their results provide an excellent basis for an improved understanding of the primary and secondary vortex flows and shock systems and will be valuable in the evolution of various mathematical models. A related study carried out on an ogive nose cylinder at  $M = 2$  in which details of the secondary nose vortex were investigated was described in an open workshop session paper authored by Oberkampf and Bartel<sup>34</sup>.

A relatively large amount of wind tunnel data obtained in the past has indicated an extreme sensitivity of body forces and moments to the surface condition and minute geometric asymmetries near the tip of the forebody. However, quantitative implications with regard to the actual flight vehicle, remain somewhat obscure not only due to the random nature of surface condition and shape but also due to the probability of strong interacting effects of Reynolds number, free stream turbulence, and model vibration. In a recent study designed to investigate the effect of stream turbulence and model vibration on surface pressure fluctuations and flow pattern "switching" between mirror image states Hunt and Dexter<sup>17</sup> performed experiments on a slender body at high angles of attack in a very low turbulence level air stream. Their results, while indicating that switching of the flow patterns with time for a rigid model was virtually eliminated in the low turbulence stream (approximately 0.01% turbulence level), also demonstrated that the surface pressures were still sensitive to model roll angle thereby emphasizing that strict control of the free stream conditions is not sufficient to guarantee results that are independent of slight model asymmetries.

### 2.2.4 Wing-Body Combinations

Turning from the isolated wing and isolated forebody to complete configurations which involve interactions of the vortex flows associated with the various components there were three papers describing experimental studies of missile type configurations. The paper by Deane<sup>18</sup> dealt with a study, at subsonic and supersonic speeds, of the interaction with cruciform wing panels of the vortices originating from the leeward side of the forebody of missile type configurations with a view towards providing additional insight needed to improve mathematical modeling of the flow not only with regard to stability characteristics but to prediction of aerodynamic loads for stressing purposes. The low speed water tunnel investigation of the vortex flow graphically illustrated the effect of the wing flow field in terminating the body generated feeding of the forebody vortices at some point upstream of the wing depending on angle of attack and some effects of interference on vortex breakdown. Neither of these phenomena are believed to be adequately accounted for in the theoretical and empirical methods currently in use and additional flow field studies, preferably at higher Reynolds numbers are needed. His wind tunnel studies at supersonic speeds illustrated the large discrepancies in the prediction of aerodynamic loads on the wing. The two other papers dealing with missile type configuration were those of Mifsud<sup>19</sup> which illustrated the strong asymmetric flow effects generated at high angles of attack and of Akcey, Richards, Stahl and Zarghami<sup>20</sup> which demonstrated the favorable effect of a wing strake on the outer wing panel similar to that observed on aircraft configurations.

### 2.3 Design Methods

There is a great deal of interest in the development of design methods to allow the inclusion of the various types of separation induced vortex flows encountered at high angles of attack. This design capability is needed for both aircraft and missiles and for a variety of applications which require accurate knowledge of the flow fields and the complete surface distribution of aerodynamic load involving separation induced vortex flows at high angles of attack. Some examples of this design requirement are wing structural design, the optimization of wing shape to provide the most efficient development of vortex maneuver lift, and the control of multiple free-vortex systems to provide adequate high angle of attack stability characteristics. Within the present state of the technology the design approach of shaping lifting surfaces to provide a prescribed optimum pressure distribution for minimum lift-dependent drag (used rather routinely for attached flow conditions) cannot be implemented for those cases where the design concept involves the utilization of vortex lift. This dilemma is associated with problems such as (1) the fact that the non-linear nature of the solution due to the floating boundary conditions and unknown strengths of the free vortex sheets precludes the superposition of elemental flows and (2) the unknown aspects encountered with regard to relating required far field conditions to required spanwise and chordwise surface pressure distributions. As a result design techniques for conditions involving vortex flows must currently rely on the use of an experimental data base and the application of theory in various "design-by-analysis" modes. In general these methods are based on the application, in various degrees and combinations, of slender body theory, three dimensional free vortex sheet or filament theories, and engineering methods based on correlations utilizing parametric wind tunnel data and simplified theoretical methods. A considerable amount of the type of information utilized in these design approaches is, of course, contained in various papers described in section 2.2. However the seven papers selected for this session on design methods provide a balance between the various types of information used in design and tend to present the information in the light of various design problems.

The session was introduced by a comprehensive review paper prepared by Lamar and Luckring<sup>24</sup> which summarized design related technology being developed under the Langley Research Center vortex flow research program. With regard to analysis capabilities required in design procedures the free vortex filament, free vortex sheet, and suction analogy methods were described and compared with experimental force and moment data for slender delta wings. Extensions of the suction analogy to arbitrary wing and strake-wing planforms in symmetrical and asymmetrical flow conditions was reviewed and comparisons with experimental results indicated it to be a reasonably accurate and economical method when only the overall forces and moments are required. Where detailed surface pressure distributions are needed the Boeing/NASA free vortex sheet method, described in section 2.2, was shown to offer considerable promise and should be further refined and extended to arbitrary configurations. With regard to an experimental data base for engineering type design methods the results of parametric wind tunnel and numerical studies were presented for a series of ogee strake-wing combinations, the favorable vortex interactions discussed and an approach to a vortex strake design procedure introduced and evaluated with regard to vortex stability characteristics. A major portion of the paper dealt with the application of various theoretical methods in the attempt to optimize the "controlled separation vortex" concept as applied to slender wings required to provide high maneuver lift capability. This "controlled" type of leading edge separation has, for some time, appeared attractive for these high lift conditions in view of the highly unlikely ability to maintain fully attached flow over slender wings. This part of the study consisted of applications of slender-body, free vortex sheet, and suction analogy methods to the drag analysis of slender cambered wings illustrating various drag reduction trends in relation to "design by analysis" approaches. As a preliminary approach to drag minimization, a special code was written which coupled an application of the suction analogy with an optimization procedure. An example of the resulting design camber and twist was presented for a slender delta wing.

Two additional papers related to the "design by analysis" possibilities offered by the new vortex flow panel methods were presented in this session. The paper of Tinoco and Yoshihara<sup>26</sup> presented a more extensive evaluation of the Boeing/NASA leading edge vortex computer program and described their recent application of the method in a preliminary study related to the search for an "optimal" camber shape to minimize the drag of slender, supercruiser type fighter wings with leading edge vortices. The results of a parametric camber and twist study and a vortex tab study provided additional evidence that some "effective" thrust could be recovered in the presence of vortex flow. The benefits demonstrated by this preliminary study were rather small and indicated that an optimization search technique and a knowledge of the lower bound drag for vortex type flow are important ingredients needed for establishing the practicability of achieving appreciable performance improvements. The paper by Hoeijmakers and Bennekens<sup>25</sup> which presented a promising extension of the free vortex sheet method which might provide more efficient application of "design by analysis" techniques has been described in section 2.2. A paper in the open workshop session presented by Nangia<sup>37</sup> presented a brief review of some thoughts with regard to the application of leading edge camber.

The next three papers presented in this session dealt primarily with semi-empirical type engineering methods and, in general, considered configurations where the non-linear fuselage forces and moments and the mutual interference effects associated with separation induced vortex flows from the various components place the prediction requirements beyond the current state-of-the-art of the available free vortex sheet and vortex filament codes described above.

Two of the papers described various degrees of semi-empirical modifications to potential flow slender body theory used to produce engineering methods which account, to some extent, for the various phenomena encountered in the high angle of attack range. Jorgensen<sup>28</sup> assembled a rather extensive summary of parametric wind tunnel studies of slender bodies of various cross sections and bodies with lifting surfaces primarily representative of aircraft configuration over a wide angle of attack range for both subsonic and supersonic speeds. The resulting data was compared with slender-body potential-flow theory, modified by a semiempirical term representing viscous-separation crossflow effects. The resulting engineering-type method provided reasonably good predictions for the bodies alone over the Mach range and for the wing-body configurations at the highest supersonic Mach number of 2.0. However, the accuracy of the predictions for the wing-body configuration deteriorates rapidly as the Mach number decreases due, at least in part, to the

fact that the free vortex sheets are not modeled and the stall development on the not-so-slender wings is not accounted for. Similar modifications of the slender-body potential-flow method to produce an engineering level prediction method for missile type configurations in quasisteady pitching motions were described in the paper by Schneider and Nikolitsch<sup>27</sup> and the rather poor agreement with experimental results are indicative of the difficulty of developing simple engineering type methods for these types of high angle-of-attack flows.

An attempt to provide additional "real flow" simulation, particularly with regard to the effects of asymmetric vortex patterns shed from the forebody, in a predictive engineering method for complete configurations was reported by Spangler, Perkins, and Mendenhall<sup>29</sup> along with some detailed flow field measurements. In the method used the nose shed vorticity was modeled by a "cloud" of vortices with origins determined by a two dimensional "cross flow" boundary layer calculation coupled with the Stratford separation criteria. The resulting vortex pattern was simplified into a small number of concentrated vortices which were used to predict the effects induced on aft components. In the zero sideslip case vortex asymmetry was induced by a small rotation of the cross flow separation points. The aerodynamic loads on the wing-strake combination are approximated by use of lifting surface methods and the leading-edge-suction analogy while those on the afterbody and tail surfaces are approximated by slender-body and "strip" methods. The limited preliminary results shown indicated that the technique appears to provide a reasonably qualitative description of the general nature of the high angle-of-attack flow patterns. While the quantitative agreement with regard to measured forces and moments was only fair, it would appear that the exploration of additional refinements to this general type of engineering approach is probably warranted.

The types of semi-empirical type engineering methods described in the previous three papers generally give little or no information with regard to the detailed aerodynamic load distributions, required for structural design of the lifting surfaces and for conditions where the surface in question is generating its own strong separation induced vortex sheets. In this regard the final paper in the session by White<sup>30</sup>, summarizes a rather extensive development of an engineering type method which predicts surface pressure distributions for relatively complicated interacting separation induced vortex flows. The resulting program, which requires certain empirical data related, for example, to flow separation criteria, vortex development and breakdown, prediction of suction peaks, etc. was applied to a wing-strake configuration and the agreement between the predicted and measured surface pressure distributions for this multiple leading-edge vortex system was reasonably good.

#### 2.4 Air Intakes

The fact that only two papers on air intakes were presented during the formal portion of the symposium was unavoidable in terms of papers submitted and was disappointing in view of the increasing demands on inlet-airframe integration imposed by the large excursions in attitude by modern fighter aircraft. Some improvement in the balance of information was realized in the open workshop session since two of the seven papers presented dealt with air intakes. Also, in view of the fact that inlet design and operation is critically dependent upon the flow fields generated by the fuselage and various lifting surfaces, the developing technology described in the other sessions in relation to the generation, trajectory, and resulting influence of vortex flows should provide valuable design and analysis methods for inlet-airframe integration.

In the first paper of the formal session Presley<sup>31</sup> reviewed the application of a computational procedure to the analysis of inlet conditions for a supersonic cruise aircraft and presented a status report on some inlet work relative to transonic maneuvering aircraft. In the supersonic study some effects of fuselage interference were predicted theoretically by coupling finite-difference, shock-capturing techniques applied (1) to the supersonic flow about an isolated fuselage forebody of arbitrary cross section at angle of attack and (2) to the flow in a mixed compression axisymmetric inlet with nonuniform upstream flow. The calculations made for a hypothetical configuration illustrated rather large fuselage interference effects and implied the possibility of significantly reducing design time and cost by application of theory to design. A brief description of some preliminary computational work under way to develop transonic methods was presented and an experimental study of airframe-inlet integration for a transonic fighter was described.

The second paper in the formal session, by Lotter and Malefakis<sup>32</sup>, discussed results obtained from subsonic wind tunnel tests of several "shielded" inlet concepts and cowl designs dictated by high angle of attack requirements. The tests, which were carried to 100° angle of attack, indicated for the configurations studied, that with regard to engine face pressure recovery either single or twin inlet locations under the fuselage were superior to under strake locations and that a rotatable cowl is promising in terms of internal performance and engine face turbulence.

In regards to the continuing effort to utilize dorsal intakes as a means to reduce foreign object ingestion, reduce duct lengths and improve area distributions the brief paper by Ridder<sup>34</sup> in the open workshop session was of interest. The study was carried out on a complete configuration but was limited to low speeds and to angles of attack below 20 degrees. Under these conditions however, it was of interest to note that a flow control vane mounted on top of the canopy was effective in reducing to an acceptable level intake flow distortion associated with the forebody vortices under sideslip conditions. The final air intake paper was a brief description by Perrier and Periaux<sup>35</sup>, in the open workshop session, of a study of low Reynolds number flow fields obtained in a water tunnel which appeared to be in qualitative agreement with some Navier-Stokes solutions.

### 3. EVALUATION AND CONCLUSIONS

#### 3.1 General Comments

The symposium was very worthwhile and contained several ingredients that might be expected to assure some definite and important influences on the directions to be followed in the future in the development of high angle-of-attack aerodynamic technology. The attendance distribution between industry, government, and university representatives was in reasonable balance as was the breakdown of paper subjects between

vehicle development experiences and basic and applied theoretical and experimental research. As a result, a valuable interaction was generated between those involved with "real world" vehicle development problems, those engaged in experimental fluid dynamics, and those carrying out the development of theoretical methods and design approaches. The importance of meetings such as this tends to be amplified by the, all too common, trend within organizations for these various groups of people to become somewhat isolated from each other. In this regard, a plea, expressed during the round-table discussion, for closer collaboration between practical aerodynamicists and experts in fundamental fluid dynamics further supported the desirability of maintaining these interactions.

If there was any major shortcoming with regard to the subject matter covered, it was probably the lack of a representative number of papers dealing directly with missiles. While much of the work in fundamental aerodynamics described during the meeting can be applied to missiles as well as aircraft, there was probably a need for more discussion of the design and operational experience with highly maneuverable missiles to help guide future research and development efforts. While additional emphasis on controllability in the high angle-of-attack range would have been useful, the fact that the subsequent Fluid Dynamics Panel Symposium (held in May 1979) dealt with the aerodynamics of controls reduced the importance of this shortcoming.

The technical content of the symposium, which will be discussed in the following sections, was very good. The progress being made with regard to understanding and controlling the flows encountered in the high angle-of-attack region and in developing the tools for design is encouraging as are the innovative concepts that are being explored for the development of high levels of maneuver lift and in controlling the many interacting separation induced vortex flows. As stated by one of the attendees "we are learning to live with separations in a rather interesting, exciting way, and I think this process will improve as both the fluid mechanics and the flight dynamics people learn to understand each other more and more."

### 3.2 Vehicle Development and Operational Experience

The session on "Configurations of Practical Application" provided an excellent forum for the discussion of the experiences gained during the development and operation of vehicles which help to define the areas where improved high angle-of-attack technology would be beneficial. The current desire to provide controllable flight to extreme attitudes and the ability, associated with the high thrust-to-weight ratios of modern fighters, to perform these maneuvers at high speeds has created a need for expansion of high angle-of-attack research and development programs in certain areas and improvements in test facilities and equipment.

The need to provide adequate aerodynamic control capability at the extremely high angles of attack and over the wide range of dynamic pressure and Mach number emphasizes the need for research on innovative aerodynamic control approaches such as, for example, those described in which various applications of the spanwise blowing and vectored thrust concepts were explored. The material presented in the session made very clear the strong dependence of the high angle-of-attack performance and stability on relatively small configuration geometry details. The strong influence of the vortex flows emanating from fuselage forebodies and wing strakes on the high angle-of-attack lateral-directional stability, departure characteristics and spin resistance is a prime example. The strong influence of nose cross-section and strake geometry, for example, on the generation, path, mutual interactions, and breakdown characteristics of these vortices leads to the need for an improved knowledge of the effects of Reynolds number and Mach number on the viscous cross flow and vortex breakdown.

The session also served to illustrate some of the needs in the area of test techniques and experimental facilities. While it was gratifying to see some results of high angle-of-attack dynamic stability derivatives extended into the high subsonic speed range, this is an area where additional research appears to be needed and where an updating of test equipment capability may be required. Also, the sensitivity of many of the high angle-of-attack aerodynamic characteristics of the strong, interacting viscous and compressibility effects emphasizes the need for improved Reynolds number simulation, particularly in the subsonic and transonic speed ranges. In this regard, the new cryogenic wind tunnels, with their high Reynolds number capabilities and their unique operating envelopes which allow the essential isolation of viscous, compressibility and aeroelastic effects, should be of considerable aid. Also with regard to facilities for the study of high angle-of-attack characteristics the possibility of applying the cryogenic concept to the design of a high Reynolds number spin tunnel might be worthy of consideration.

### 3.3 Flow Field Characteristics

It was made rather clear during the symposium that a considerable amount of detailed flow knowledge is being generated for both lifting surfaces and bodies of revolution for both subsonic and supersonic speeds. These experimental investigations are providing important information for use in theoretical modeling and in evaluating the resulting theories. An example of the progress being made, with regard to slender wings, was the improved definition of the combined secondary and trailing-edge vortex system which has a rotation opposite that of the leading-edge vortex and the subsequent success of the free vortex sheet theoretical model in predicting this type of flow.

Additional studies dealing with the fundamental aspects of the strake induced stabilization of the main wing panel vortex flow would be valuable as would research to define the effects of Reynolds number and Mach number on the vortex breakdown characteristics for various types of vortex systems in both symmetrical and asymmetrical flow situations.

The reported study of the flow details involved in the generation of separation induced vortex flow on wings with rounded leading edges will be useful in modeling this type of Reynolds number dependent flow. This type of study needs to be extended to higher Reynolds numbers and Mach numbers. Also in connection with viscous dependent flows detailed flow studies to better define the mechanisms involved in asymmetric vortex shedding from forebodies would be of interest.

### 3.4 Theoretical Methods

Because of the strong viscous effects involved in high angle-of-attack aerodynamics, accurate theoretical methods are difficult to formulate. However, for certain cases, such as the slender sharp leading-edge wings with separation induced free vortex sheets originating at the sharp edge, inviscid schemes can provide useful results. In this regard, the recent extensions of the leading-edge suction analogy method to arbitrary planforms and multiple vortex flows has provided a reasonably accurate and economical method when only the overall forces and moments are required and the approach should be explored for the various dynamic derivatives. The prediction of the complete surface pressure distribution is, of course, required for many of the aerodynamic and structural design and analysis requirements and again inviscid modeling can provide useful results for the relatively sharp edge cases. The emphasis indicated by the symposium papers on the use of completely three-dimensional modeling of the vortex flow as opposed to the more limited slender-body methods, was an encouraging sign. Although somewhat limited with regard to the configurations that can be currently treated, the free vortex sheet methods described appear to be very promising. Continued development and improvements in efficiency should be encouraged and the method extended to multiple vortex systems. The various discrete - vortex approaches described are also of considerable promise and should be more fully developed. Before theoretical methods are completely satisfactory, the effects of the secondary vortex and other viscous dominated effects such as those associated with the vortex core must, of course, be incorporated. For the general case, the three-dimensional boundary layer effects and separation criteria need to be incorporated to allow prediction of the Reynolds number sensitive flow on round leading-edge wings.

While some reference was made to modeling of vortex breakdown, it is an area where a considerably greater effort appears to be needed. The strong influences of asymmetric breakdown on lateral-directional stability, for example, emphasizes the fact that mathematical modeling of aircraft at high angles-of-attack must include these effects.

Notably missing from the symposium were examples of theoretical modeling of the high angle-of-attack flow at transonic and supersonic speeds. While some reference was made to successful applications of the suction analogy, it only provides overall forces and extension of the vortex sheet modeling to high speeds should be encouraged. A particularly important need in this regard is the development of a mathematical model which accounts for both the wing strake vortex flow and the attached transonic flow on the main wing panel. Regarding the supersonic flow modeling for the thin wing subsonic edge case, the assumption frequently used is that leading-edge separation can be accounted for by simply eliminating the leading edge singularity. This of course, is unrealistic and methods for incorporating the associated vortex flow need to be developed for arbitrary configurations.

For bodies at high angle-of-attack, inviscid modeling approaches are of limited applicability and improved compressible viscous flow modeling methods are needed especially for the general case of arbitrary cross sections of practical application to aircraft fuselages. Such methods are needed not only with respect to aircraft stability and tail loads, but with regard to air inlet characteristics. As in the case of lifting surfaces, both static and dynamic conditions should be modeled.

While reasonable progress is being made in the development of theoretical methods for rather idealized isolated components the ability to calculate the aerodynamic derivatives required to predict the performance, handling qualities and stall-spin characteristics of air vehicles in the high angle of attack range is still in a rather primitive state.

### 3.5 Design Approaches

There are many design considerations involved in providing efficient and controllable flight at high angles-of-attack and for various reasons, the present state-of-the-art is such that "design by analysis" methods must be resorted to. Regarding the interest in optimizing the vortex maneuver lift for slender super-cruiser type aircraft progress is being indicated in the application of the free vortex sheet modeling methods in the laborious "design by analysis" mode aided in certain cases by the suction analogy. Considerable improvements in these techniques will probably be developed and with sufficient ingenuity on the part of the aerodynamicist improved designs will evolve. However, before efficient optimum design procedures can be developed, some fundamental fluid dynamic questions must be answered regarding such items as: (1) the real lower bound of the lift dependent drag for vortex wakes which originate from both leading- and trailing-edges and (2) how to relate the required far field conditions to the corresponding optimum lifting surface pressure distribution which, for this type of wake, is no longer defined only by its spanwise distribution and will result in a camber surface that no longer is non-unique.

In connection with the design problem associated with assuring satisfactory handling qualities over the extreme angle of attack and Mach number ranges for arbitrary configurations involving complicated interacting vortex flows, methods such as the empirical engineering methods described will probably be resorted to for some time. However, more rigorous theoretical approaches, such as the free vortex sheet methods and various solutions of the Navier-Stokes equations should continue to be explored and developed.

## 4. ACKNOWLEDGEMENTS

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Program Committee - Members of the Fluid Dynamics Panel who served as members of the program committee were:

Dr. W. J. McCroskey (Chairman) U.S. Army AMRDL; M. I'Ing. General A. Auriol, ONERA; Dr. J. E. Green, RAE; Prof. Dr. F. J. Hindelang, FLR; Dr. K. J. Orlik-Ruckemann, NAE; Dr. G. G. Pope, RAE; and Prof. Dr. J. L. van Ingen, Delft University of Technology.

In addition, the Flight Mechanics Panel was represented by M. Poisson-Quinton, ONERA

Panel Executive - Mr. R.H. Rollins, II, assisted by Melle Anne-Marie Rivault.

Meeting Coordinator - Mr. F. Klouman, Norwegian Defence Research Establishment.

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