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Vortical Flows Research Program of the Fluid Dynamics Research Branch

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NOMENCLATURE

B-L:	Boundary layer
L:	Typical length scale
M:	Mach number
Re:	Reynolds number, UL/ν
R_Γ:	Vortex circulation Reynolds number, Γ/ν
r:	Vortex core radius
U,V,W:	Mean velocity in the X,Y,Z directions, respectively
U_e:	Free-stream velocity in the wind tunnel
U_o:	Velocity difference across mixing layer
u', v', w':	Fluctuating velocity components in the X,Y,Z directions, respectively
u.v.w:	Instantaneous velocity in the X,Y,Z directions, respectively
V.G.:	Vortex generator
X, Y, Z :	Cartesian coordinates for streamwise, normal, and spanwise directions, respectively.
Γ:	Overall vortex circulation
θ:	Boundary layer momentum thickness
ν:	Kinematic viscosity
ρ:	Density
ω_x:	Streamwise vorticity
—:	(overbar) Time-averaged quantity

SUMMARY

This report summarizes the research interests of the staff of the Fluid Dynamics Research Branch in the general area of vortex flows. A major factor in the development of enhanced maneuverability and reduced drag by aerodynamic means is the use of effective vortex control devices. The key to control is the use of emerging computational tools for predicting viscous fluid flow in close coordination with fundamental experiments. In fact, the extremely complex flow fields resulting from numerical solutions to boundary value problems based on the Navier-Stokes equations requires an intimate relationship between computation and experiment. The field of vortex flows is important in so many practical areas that a concerted effort in this area is well justified. A brief background of the research activity undertaken is presented in this note, including a proposed classification of the research areas. The classification makes a distinction between issues related to vortex formation and structure, and work on vortex interactions and evolution. Examples of current research results are provided, along with references where available. Based upon the current status of research and planning, speculation on future research directions of the group is also given.

1. INTRODUCTION

Vorticity and vortex flows are the fundamental entities that govern both the microscales of turbulence and the macroscales of galaxies (ref. 1). Somewhere in between are those vortex flows that arise in practical aerodynamics. The persistence of vortices and their remarkable effects on fluid flows have provided interesting research subjects for decades, as evidenced in many of the photographs compiled by Van Dyke (ref. 2). However, it is somewhat surprising that the details of this most important class of flows are still not very well understood (ref. 3). In practical aerodynamics, vortices are unique in that they are useful as well as a nuisance.

The principle of boundary layer separation control by vortex generators has been used on aircraft wings since the 1940s. It involves the generation of discrete longitudinal vortices near the surface to enhance the mixing between the higher-momentum external stream and the boundary layer. However, with higher demands on aircraft performance, attention has also been focused on the interaction of a single, relatively strong vortex with the wing boundary layer and wake. Highly maneuverable fighter aircraft utilize the vortex from a canard or strake to suppress or control boundary layer separation on the wing (often induced by the presence of shock waves) in order to sustain the lift necessary for maneuverability.

Apart from the well known problems of wingtip vortex decay, vortices are also found to adversely affect aircraft performance. Examples include energy-draining secondary flows in wing/body junctions and curved ducts. In rotorcraft, the interaction of a blade-tip vortex with the following blade results in a complex acoustic and aerodynamic response. The catastrophic effects of vortex shedding and bursting over delta wings and bodies of revolution at high incidence have yet to be fully appreciated.

At least two parameters are generally required to characterize the relative size and strength of a vortex. An example of the relevant parameters for wingtip vortex decay would be the vortex Reynolds number, Γ/ν, and the relative vortex angular momentum, Γ/rU. Additional parameters will be introduced for particular flow problems when a vortex evolves in the presence of other effects. One of the overall goals of the vortical flow research program is to assess the influence of parametric variations.

The research topics described here belong to a class of vortical flows that can be characterized as weakly three-dimensional (3-D) and slowly evolving - an ideal prototype for the study of complex 3-D viscous flows. By using these flows as test cases for exhaustive experimental and computational analyses, we will be in a better position to attack those practical problems of vortex control that have been so intractable. The overall goal is to improve the basic understanding of such flows by using the new generation of experimental and computational tools now becoming available.

The current research effort aims to study (1) the production and structure of vortices associated with aerodynamic vehicles, and (2) how such vortices can affect vehicle aerodynamics through interaction with surfaces, viscous and turbulent flow zones, or other vortices.

Figure A1 (in the appendix) presents a summary outline of these two main research areas, and provides a framework for the discussion of current and planned research presented in Sections 2 and 3.

Vortex formation, the first research area identified in figure A1, includes four mechanisms for the formation of discrete regions of concentrated vorticity. It is believed that vortices produced by each mechanism will exhibit common properties, so that the proposed classification should form a useful basis for organizing our studies. The first two mechanisms, skew-induced and Reynolds-stress-induced vortex formation, are easily identified from corresponding terms in the Reynolds-averaged form of the vorticity transport equations. Skew-induced vortices are generated in the 3-D flow about a body near a ground plane ("horseshoe vortices"), in S-shaped ducts, and when a jet of fluid is injected with a component normal to a streaming flow. Stress-induced vortices are less commonly observed; a typical example of their formation is in long, streamwise, turbulent, corner-flow regions.

Instability-generated vorticity is observed, for example, in viscous flow over concave surfaces. The fourth mechanism, vortex formation caused by the lift on an aerodynamic surface, could also be classified as skew-induced, but because of the particular importance of wing-shed vortices for the applications of interest to the current researchers, this mechanism has been separated from the other cases of skew-induced vortex generation. For example, the details of the process of formation and persistence of wingtip vortices have been studied to alleviate landing hazards for small aircraft caused by the earlier landing of larger craft. Also, observations of catastrophic "breakdown" of leading-edge vortices over delta-wing planforms has led to intensive study of the formation, structure, and stability of such vortices.

The second significant research area, vortex evolution and interaction, is divided into four major categories. The classification covers problems of direct interaction between adjacent vortices, the effect of mean perturbations on vortex behavior, the effects of turbulence, and the interaction of a vortex with a solid surface.

The flow near a wing-body junction will serve as an example to illustrate the vortex-related phenomena that occur in practical situations, and how such phenomena fit into the proposed classification scheme. Initially, the skewing of the oncoming flow near the leading edge of the wing generates the familiar horseshoe vortex in the wing-root region. Interaction between the (generally turbulent) corner flow and the vortex ensues as the vortex evolves; mean perturbation of the vortex due to streamwise pressure gradients in the trailing-edge region over the wing may also be observed. Downstream of the wing trailing edge, the two "legs" of the horseshoe will interact with each other and with the surface boundary layer. In this example, understanding the mechanism of skew-induced generation, vortex-turbulence interaction, the influence of mean perturbations, and the interaction of adjacent vortices is required to encompass the overall influence of the vortex on the global flow properties.

Issues related to the evolution and interaction of vortices have been separated from those related to vortex formation and structure in the hope that the two items will often be uncoupled and may be separately analyzed. It is recognized that such an idealization is often a poor approximation, as in the case of the formation of streamwise vorticity in a corner flow. Here, the vortex is formed because of the turbulence stresses in the corner region; consequently the vortex must interact intimately with the turbulence to produce the observed structure. Notwithstanding such coupling, it still appears useful to treat the formation and evolution of vortices as separate topics for many applications.

Examples of the current research efforts of the group are presented in the next section. The section starts with a description of the operating parameters and classification of the research projects as described in figure A1. It will be noted that the current work covers both of the major areas of vortex formation and evolution, with most of the current effort in vortex evolution and interaction. Each research area is described by a few paragraphs and figures; references are also cited for further details.

2. SAMPLES OF VORTICAL FLOW RESEARCH

Some completed research projects on vortical flows are described briefly in this section. The operating parameters and classification of each individual vortical flows research area are given in figure A1 and table A1 in the appendix.

2.1 Interaction Between a Longitudinal Vortex and a Separated Turbulent Boundary Layer

An experimental study has been completed on the effect of a single longitudinal vortex on a transonic, separated, turbulent boundary layer (refs. 4 and 5). The vortex was generated by a half-delta wing mounted at the front end of an axisymmetric "bump" model (fig. 1a). At subcritical Mach numbers, the adverse pressure gradient over the back of the bump was severe enough to produce a small region of boundary layer separation. At postcritical Mach numbers, the boundary layer separated at the shock location, just downstream of the bump apex. A detailed flow-visualization study was conducted using vapor-screen and surface oil-flow techniques. In addition, surface pressures and detailed mean flow and turbulence measurements were obtained using a two-component laser velocimeter. As expected, the overall effect of the vortex was to reduce the region of boundary layer separation. At precritical Mach numbers, the vortex delayed or eliminated boundary layer separation on the downwash side and enhanced it on the upwash side. However, at postcritical speeds, the effect of the vortex was to reduce the extent of boundary layer separation throughout the region of interaction. The boundary layer turbulence in both cases was found to reorganize accordingly, although in a complex manner.

In the surface oil-flow visualization photographs (figs. 1b-d), the flow is from left to right and the vortex is rotating in a counterclockwise direction viewed from upstream. At a precritical Mach number of 0.7 (fig. 1b), the effect of the vortex is to delay separation on its downwash side and to move it upstream on the upwash side. The resulting distorted separation line forms a clockwise-rotating focus on the surface. When the Mach number is increased to that just below the critical ($M = 0.8$), another focus appears on the surface with a counterclockwise rotation (fig. 1c). With a further increase in Mach number, the whole separation moves upstream to the shock location. At $M = 0.862$, the effect of the vortex is to perturb the highly sensitive shock-wave/boundary layer interaction such that the shock wave and the ensuing separation are moved downstream locally. Once again the asymmetric separation forms a focus, but this time it is dominated by a counterclockwise rotation (fig. 1d). Thus, even qualitatively, there are severe Mach number effects which add to the complexity of this interaction.

The results from this study, the first of its kind at transonic speeds, will be useful for assessing vortex-generator performance in compressible flow. This interaction is also an extremely challenging test case for the development and testing of computational methods.

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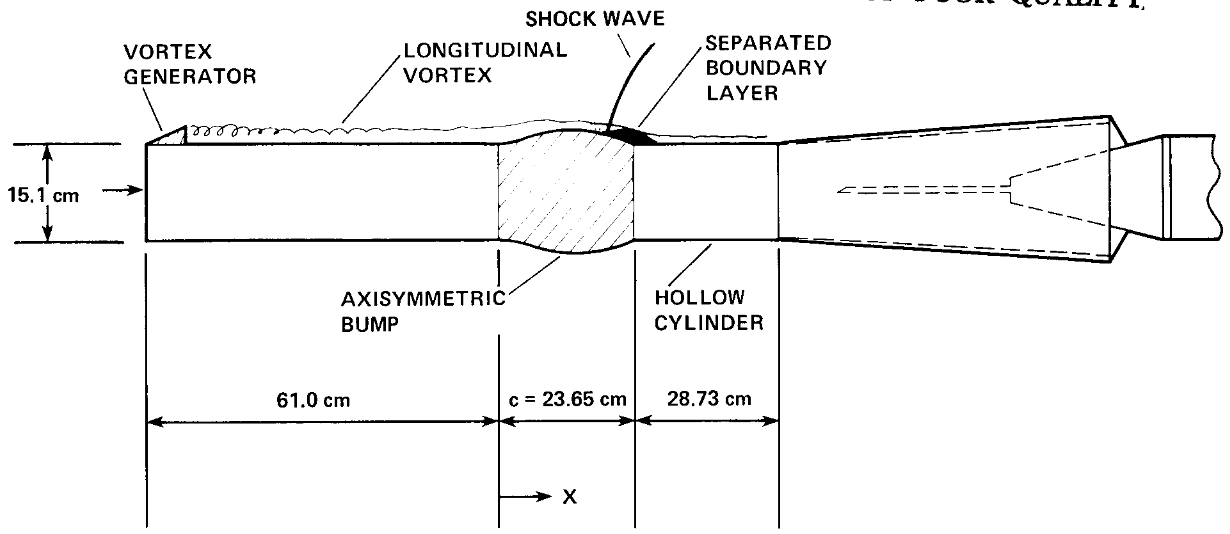

Fig. 1a. Schematic of experimental model

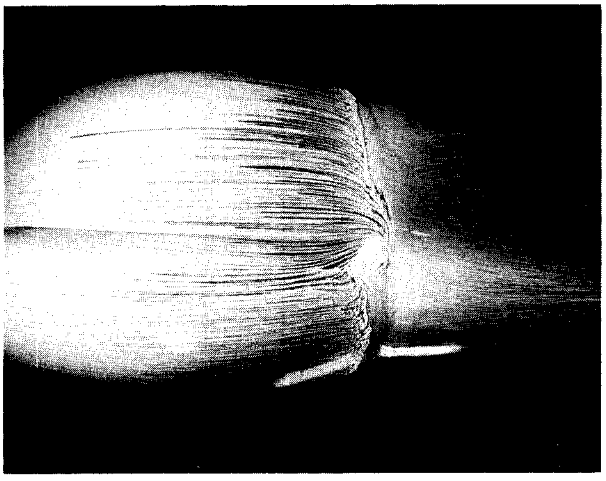

Fig. 1b. Oil-flow visualization, M = 0.7

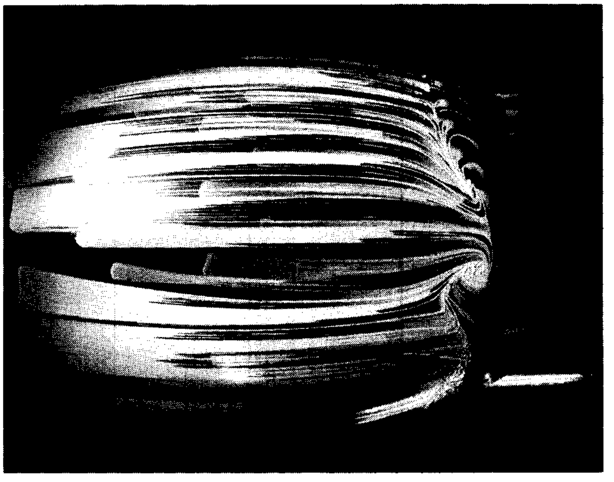

Fig. 1c. Oil-flow visualization, M = 0.8

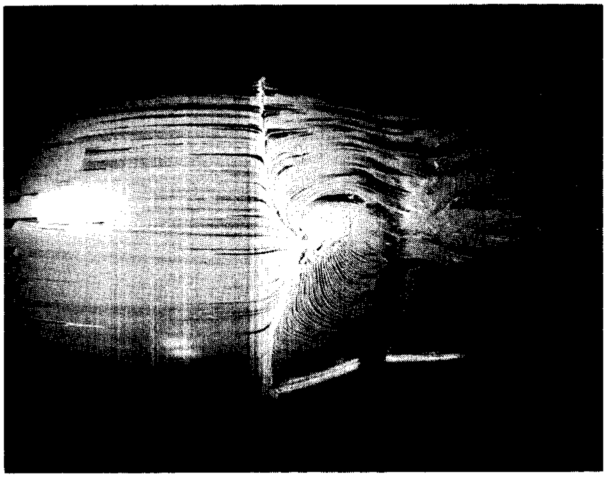

Fig. 1d. Oil-flow visualization, M = 0.862

2.2 Flow-Visualization Studies of Vortex/Wing Interactions

Although the vortex/wing interaction problem has been the subject of much attention over the years, most of the efforts have concentrated on the measurement and prediction of induced loads on the wing. The prediction methods do not perform well when the vortex lies very close to the wing surface, wherein the viscous interaction between the vortex and the boundary layer produces a complex, 3-D flow field. In the past, no attempt was made to study the details of this viscous interaction, which must be adequately modeled if the performance of the wing is to be predicted accurately. The main objective of the present investigations was to study the 3-D effects induced by a streamwise vortex on the boundary layer of a two-dimensional (2-D) wing.

The interaction of a streamwise vortex with a laminar boundary layer on a 2-D wing has been studied in two water flow facilities (McLachlan, in preparation and ref. 6). In both cases, the main wing and the vortex generator (finite span wing at angle of attack) had NACA 0012 profiles.

In Figure 2a, flow visualization was by means of the laser-induced fluorescence method. A crossflow plane view, aligned with the wing trailing edge, is shown. The counterclockwise rotating vortex and the wing upper-surface boundary layer material are marked in the figure. The main wing is at 0° angle of attack and the Reynolds number, based on chord, is 4500. The principal effect of the vortex is to induce a cross flow in the wing boundary layer such that the boundary layer is thinner on the downwash side compared to the upwash side. Since the cross flow also has to satisfy the no-slip condition, opposite signed vorticity is produced in the boundary layer. This opposite-signed vorticity is lifted up and rolled into a secondary vortex by the effects of the main vortex.

Figure 2b shows a plan view of the interaction with the main wing at an angle of attack of 5° and a Reynolds number of 50,000. Visualization was by dyes; the vortex, with a clockwise rotation viewed from upstream, and the wing boundary layer are marked. The effect of the vortex in this case is to induce primary boundary layer separation on the upwash side as evidenced by the diffusion of surface dye in the upstream direction. In practice, this would result in a strong rolling moment on the wing.

It was evident from these studies that significant viscous effects occur when the vortex is in close proximity to the wing, the nature and extent of which are dependent on the angle of attack of the main wing (ref. 6). These qualitative studies have proved extremely useful in directing the more detailed quantitative investigations.

Fig. 2a. Vortex/Wing interaction - crossflow plane view

Fig. 2b. Vortex/Wing interaction - plan view

2.3 Performance of a Double-Branched Vortex Generator

It has been traditional to use vortices generated by half-delta wings or finite-span wings for experimental purposes, mainly because such generators are relatively easy to fabricate and install. Furthermore, these generators (at prestall angles of attack) have been shown to produce a vortex with minimal (undesirable) secondary flows. However, it is not possible to independently vary the vortex location and strength conveniently with this type of generator. In assessing vortex/surface interactions, in addition to the usual vortex Reynolds number, another important parameter is the separation distance between the surface of interest and the vortex. In order to begin evaluation of the effect of variation of this distance on a vortex/surface interaction flow field, a double-branched vortex generator has been constructed and tested (ref. 7). This vortex generator is particularly suitable for parametric studies as it can be easily repositioned without altering the characteristics of the shed vortex. Some control of vortex circulation is also possible.

As shown in figures 3a,b and c, the basic configuration of this generator consists of two adjacent, identical airfoils set at opposite angles of attack. The two inboard trailing vortices roll up together quickly to form a single, fairly strong line vortex with its axis parallel to the free stream. An optimal configuration was determined, and is illustrated in the figure.

Secondary flows from the outboard portion of the wings were minimized with end plates to the extent where they would not be expected to interfere with the main vortex interaction. Secondary flows could be further minimized by the use of larger end plates, or by twisting the airfoils so that the angle of attack is small near the outer ends. Chord extensions were added to the inner trailing edges of the wings. The purpose of the chord extensions was to vary the circulation along the span of the wings such that near the inner edges there was a sharp, nonlinear transition to the region of zero circulation at the axis. This steeper gradient in the circulation caused higher peak vorticity; that is, a more tightly rolled-up vortex. The circulation of the primary vortex in this case was approximately twice that obtained with half-delta wings used in the previous investigations (refs. 4,8 and 9). Note that the circulation may be further increased by installing longer chord extensions or by using wing sections which produce a higher lift coefficient at relatively low Reynolds numbers.

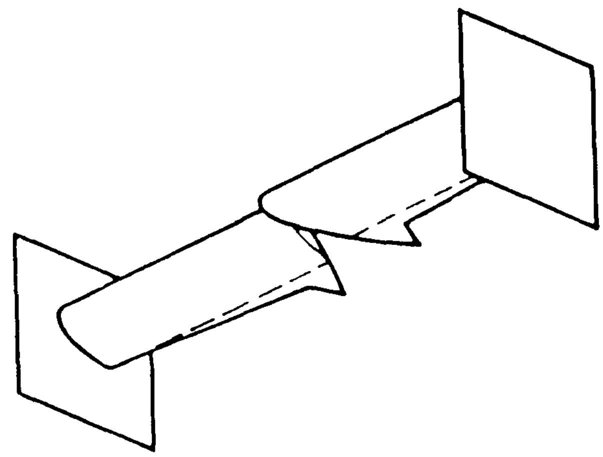

Fig. 3a. Double-Branched vortex generator

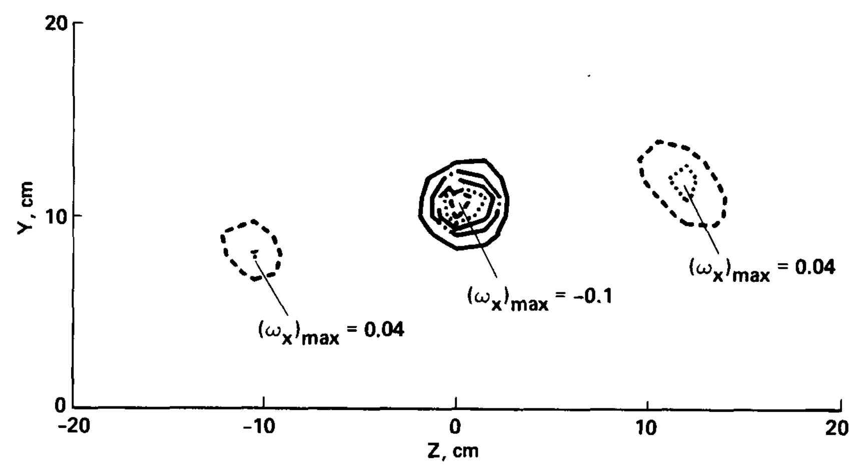

Fig. 3b. Streamwise vorticity contours

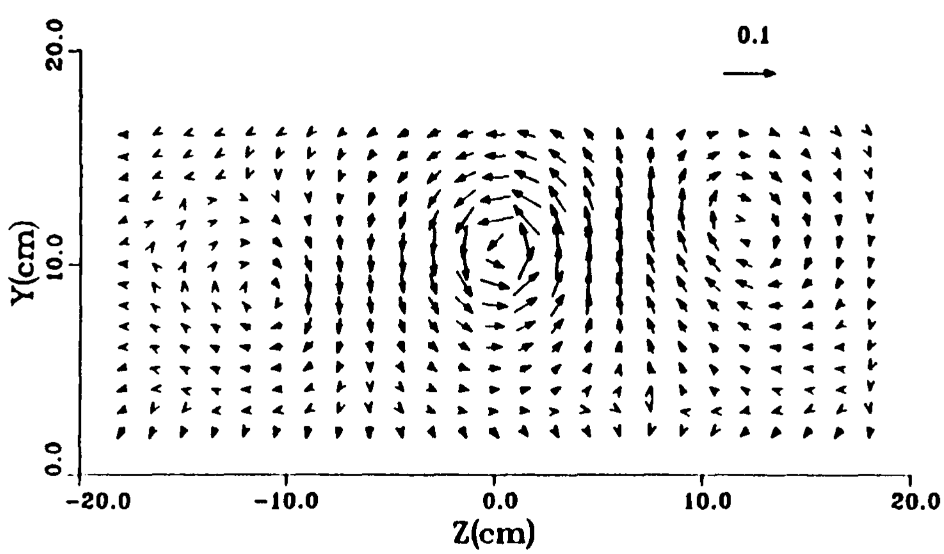

Fig. 3c. Crossflow velocity vectors

2.4 An Experimental Study of a Longitudinal Vortex Interacting with a Plane Turbulent Mixing Layer

The specific objective of the present study was to investigate the structure of an artificially generated vortex and its effect on the mean and turbulence properties of a well-defined and relatively simple free turbulent shear flow. In particular, changes in the vortex and shear flow structure were to be investigated as the vortex approaches and then actively interacts with the shear layer. The type of shear flow selected for this investigation was a two-stream turbulent mixing layer, since the asymptotic behavior of this flow is well defined. Also, the relatively fast growth rate of the mixing layer would enable a complete study of the influence to be made, from the situation where the vortex rides above the mixing layer to active interaction with the mixing layer fluid. This configuration would also make it easier to define initial conditions for parallel computational studies.

The first phase of this subsonic investigation has been completed (ref. 8). The two-stream mixing layer was generated in a small blower tunnel by installing a sheet of dense foam over the upper half of the last screen and dividing the flow in the contraction with a splitter plate. This arrangement produced two uniform streams with a velocity ratio of 0.5. A longitudinal vortex was generated by mounting a half-delta wing vortex generator in the wind tunnel settling chamber (fig. 4a). A detailed flow-visualization study was conducted by illuminating white, mineral oil smoke with a sheet of laser light. (fig. 4b). Smoke was injected at the base of the vortex generator to mark the vortex, while the mixing layer was seeded by triggering a pulse of voltage on a wire coated with oil, located at the splitter-plate edge. Measurements of the mean-flow and turbulence quantities were made using X-wire probes. The vortex induced strong secondary motions and small increases in the normal stresses within the mixing layer. At the upstream locations, the vortex was found to develop some normal stresses within the core region (fig. 4c). The normal stresses then combined with the appropriate mean velocity gradients to generate shear stresses farther downstream. On the whole, though, the results suggest that there was no active interaction between the vortex and the mixing layer; i.e., the vortex did not appear to entrain any mixing layer fluid. This was at least partly due to the relative weak strength of the vortex and its distance from the mixing layer.

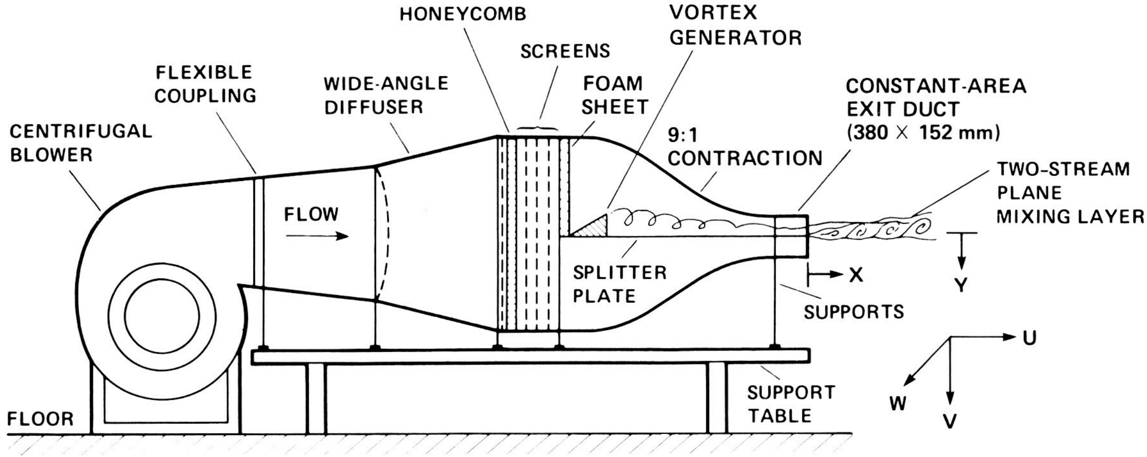

Fig. 4a. Schematic of experimental set-up

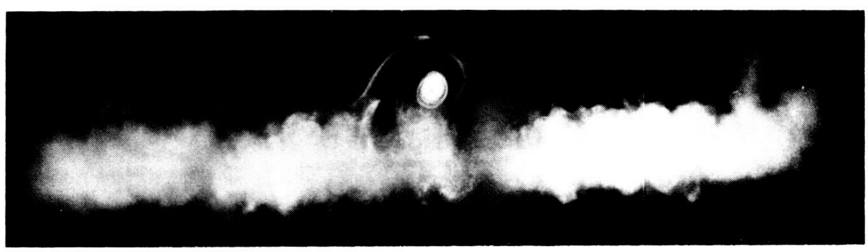

Fig. 4b. Smoke flow visualization, X = 178 mm

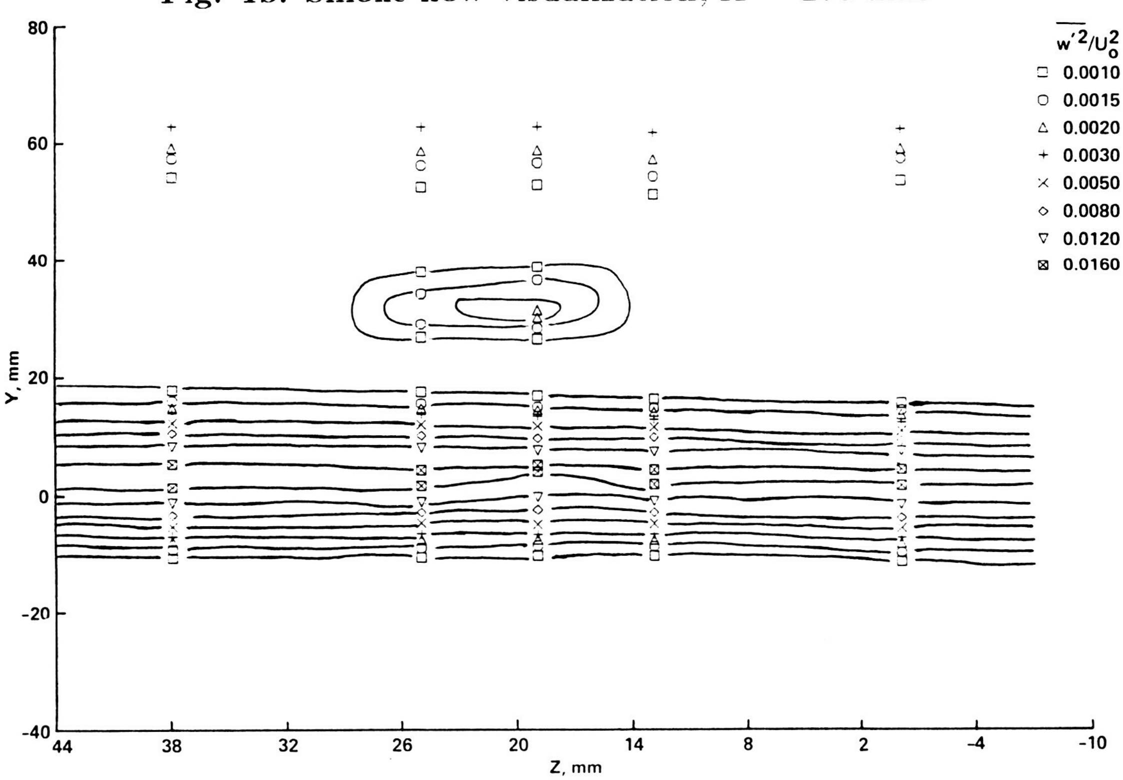

Fig. 4c. Spanwise fluctuation ($\overline{w'^2}/U_o{}^2$) contours at X = 229 mm

2.5 Interaction Between a Vortex and a Turbulent Boundary Layer in a Streamwise Pressure Gradient

The interaction of a single streamwise vortex with a turbulent boundary layer has been studied experimentally, including the effects of adverse pressure gradient (ref. 9). Mean velocity, turbulence stresses, and skin friction were measured and analyzed to determine the effects of the boundary layer turbulence on the vortex, and also to examine the changes in boundary layer structure caused by the vortex. Particular effort was devoted to the characterization of the vortex properties based on measured cross-flow velocity components.

The experiments were performed with a boundary layer momentum thickness Reynolds number in the range 2,000 to 10,000, and a vortex with a circulation Reynolds number of about 10,000 in the incompressible flow regime. The flow under study may be characterized as weakly 3-D since maximum flow angles never exceed 15° relative to the mean flow direction. Figure 5a shows a schematic of the experimental configuration, which employed a small half-delta wing vortex generator positioned within the test boundary layer and upstream of a region where the pressure gradient could be controlled. Properties of the vortex, including overall circulation, core position, and core size, were obtained from the vorticity contours computed from the measured cross-flow velocity components. Figure 5b shows a typical vorticity contour for the constant-pressure interaction.

One observation from the study was that an initially round vortex tends to flatten at downstream stations. In figure 5c, the ratio of vertical and spanwise vortex dimensions, obtained from the sort of data shown in figure 5b, is plotted against the streamwise position. The results indicate that round vortex cores were present initially, but the boundary layer and proximity of a solid surface can tend to flatten the vortex. This effect was accentuated in the presence of an adverse pressure gradient due to an increased core growth rate for this case. One possible explanation for the observed core flattening is "meandering" of the vortex. A companion experiment was performed to examine this issue, as is summarized in the next section of this report.

Measurements of turbulence stresses (not shown here) have indicated that the turbulence is strongly perturbed compared to the 2-D boundary layer without an imbedded vortex. There is evidence that simple turbulence models should suffice for calculation of the Reynolds shear stresses, but that more complex models may be required to compute the evolution of the vortex.

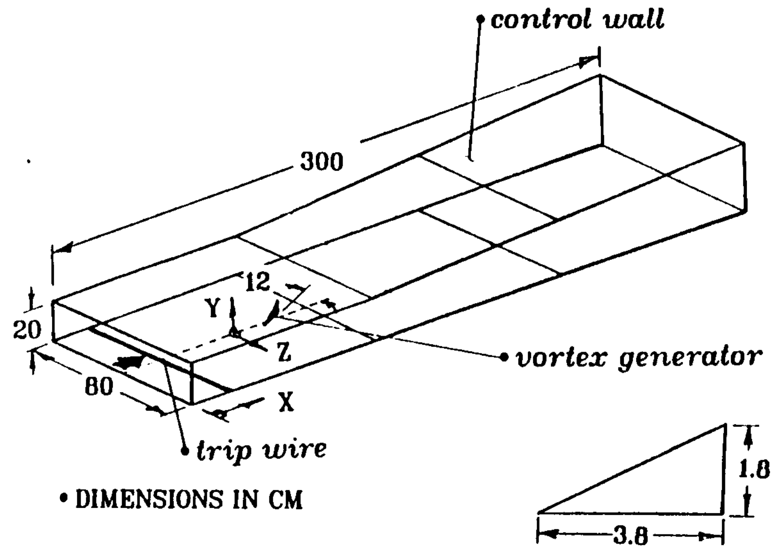

Fig. 5a. Schematic of experimental configuration

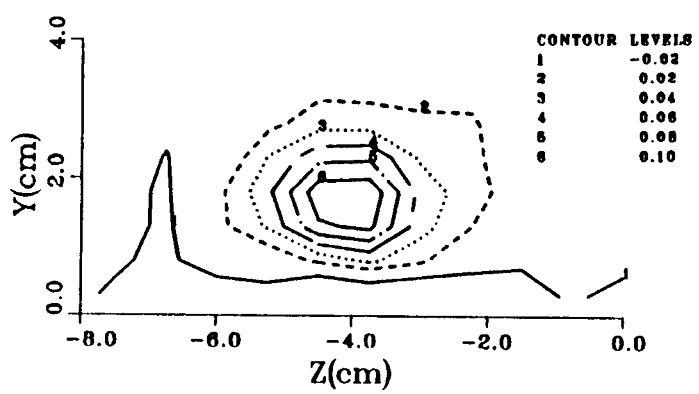

Fig. 5b. Streamwise vorticity contours $(\omega_x/U_e, cm^{-1})$

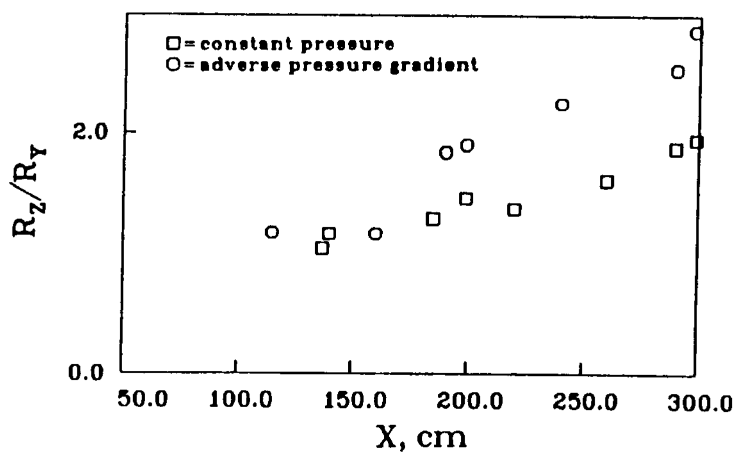

Fig. 5c. Vortex core shape variation with streamwise position

2.6 Meander of a Vortex in a Turbulent Boundary Layer

The effects due to vortex meander in a turbulent boundary layer have been investigated experimentally (Westphal and Mehta, in preparation) for a vortex/boundary layer interaction of the type discussed in the previous section. It has been proposed that vortex meander, defined as a quasi-steady motion of the vortex in a plane parallel to the nearby surface, is an inherent feature of the vortex/ boundary layer interaction. The present experiment was designed to examine the effects of forced meander on distributions of mean velocity and Reynolds stresses. Vortex meander was simulated by forcing a periodic lateral translation of the vortex generator at a very low frequency ($\sim$ 1 Hz) using a motorized Scotch yoke mechanism. Figure 6a shows the half delta-wing vortex generator and oscillator mechanism. The effect of this forced meander was characterized by measurement of the apparent mean velocities and Reynolds stresses at two streamwise stations, for cases with and without forcing. This study is particularly relevant to the observation of flattened vortex cores in previous work (ref. 9), which could simply be the manifestation of vortex meander.

The results shown in figure 6b indicate how the forced meander indeed caused a flattening of the vorticity contours at a station where they were originally round. Furthermore, the Reynolds stresses, especially $\overline{u'w'}$, were also affected significantly, mainly through contributions from the individual production terms. In figure 6c, the $\overline{u'w'}$ contours at an upstream station with and without forcing are shown, and a 50% increase in the measured peak value of $\overline{u'w'}$ was observed which can be attributed to the forcing. Farther downstream, where the vortex core had substantially diffused and the mean velocity gradients were smaller, the additional (apparent) stresses were found to be much smaller. The study has demonstrated that meander of vortices with relatively large peak core vorticity can be expected to produce apparent flattening and strong production of apparent stresses, particularly $\overline{u'w'}$, but that vortices with larger, more diffuse cores may not necessarily produce a measurable $\overline{u'w'}$ perturbation.

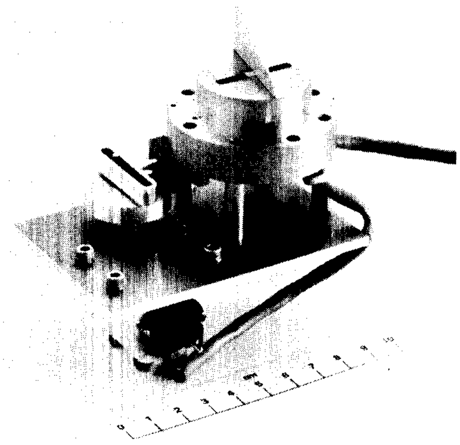

Fig. 6a. Oscillating vortex mechanism

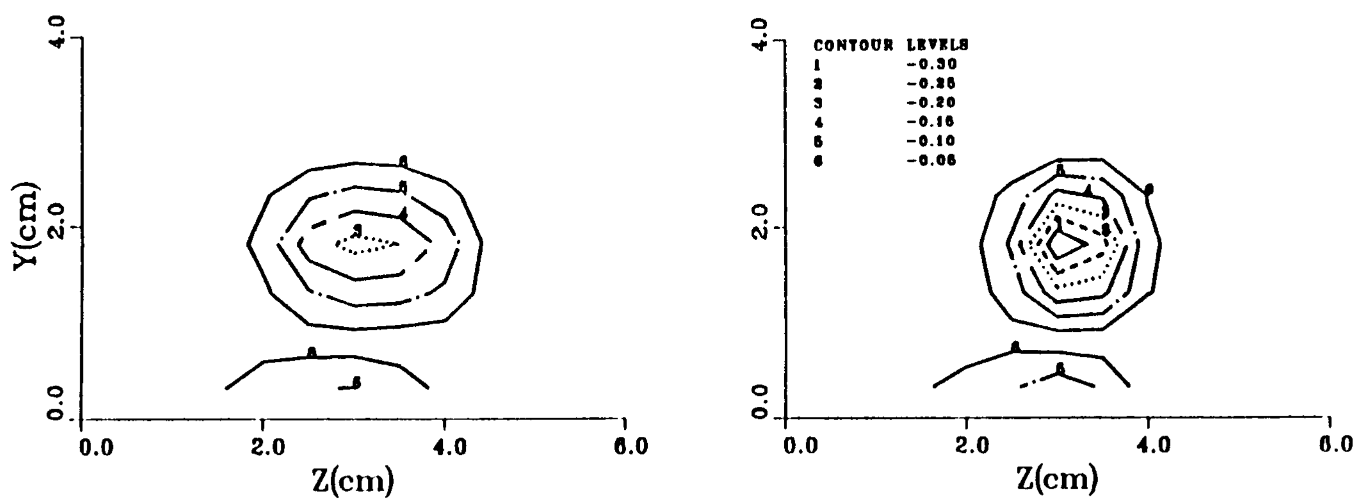

Fig. 6b. Streamwise vorticity contours ($\omega_x/U_e, cm^{-1}$)

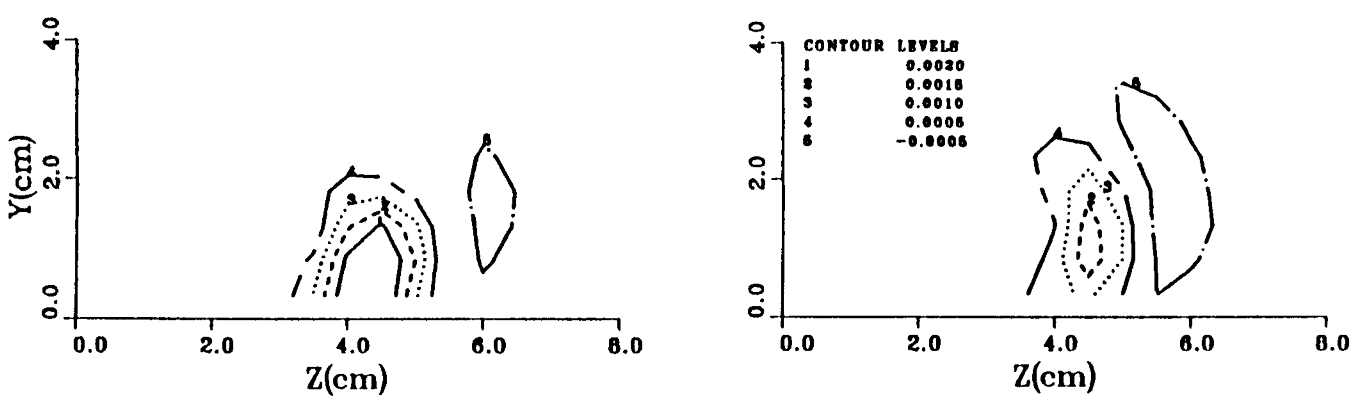

Fig. 6c. Contours of turbulence secondary shear stress ($\overline{u'w'}/U_e{}^2$)

2.7 Vortex Flows on Bodies of Revolution

The flow around slender bodies of revolution is a fundamental element of aerodynamics which has application to most flight vehicles and has been intensely studied for decades. Past studies have demonstrated that the vortex wake structure which develops on most slender bodies is primarily dependent on the angle of attack, tip geometry, fineness ratio of the body, and, to a lesser degree, Mach and Reynolds numbers.

The vortical flow development on an ogive cylinder of a fineness ratio of 3.5 is a typical example of the flow past a slender body of revolution. At 0° angle of attack, the flow is axisymmetric. A minute increment in angle of attack causes two steady, symmetric longitudinal vortices to form on the lee side of the body. The strength of these primary vortices continues to increase with increasing angle of attack, and evidence of the formation of secondary vortices of opposite sense to the primary vortices may be found near the surface of the ogive cylinder. At a critical angle of attack of approximately 35°, an asymmetric disturbance causes a dramatic change in the orientation of the primary vortices to an new, stable, asymmetric state. For angles of attack greater than 60°, the flow becomes unsteady and as the angle of attack approaches 90°, a periodic vortex "street" forms in a manner similar to that observed on a 2-D circular cylinder.

This complex flow field is presently being investigated using a combined computational and experimental approach (ref. 10). Emphasis is being placed on the near wake region in an effort to determine the mechanisms which affect the growth and stability of the vortical flow.

Smoke flow visualization of the flow past an ogive-cylinder at 30° angle of attack is shown in figure 7a. An array of 60 smoke filaments produced from a rake located upstream of the model impinge on the centerline of the ogive cylinder. Some of the filaments which pass above the tip are stretched and entrained by the primary vortices as the flow develops along the body. Laser sheet illumination of the cross-flow plane clearly shows the steady longitudinal vortices which form on the lee side of this body.

A companion 3-D, incompressible Navier-Stokes computation of the same configuration, but at lower Reynolds number, is presented in figure 7b. Five arrays of particles are released in the windward boundary layer. The path lines formed by these particles show the initial roll-up of half of the symmetric vortex pair. The experimental and computational results show promising qualitative agreement.

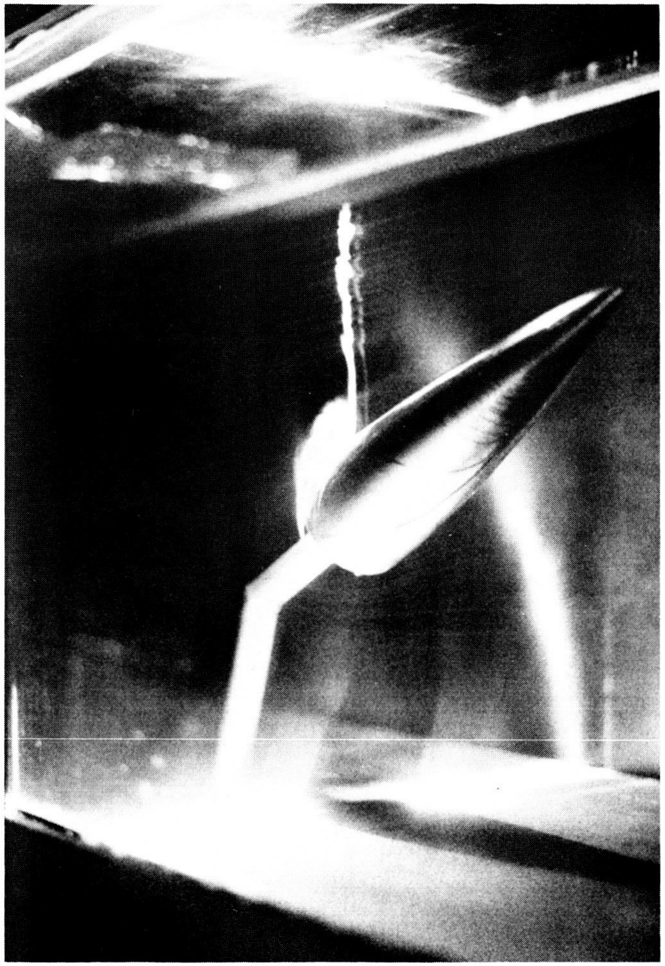

Fig. 7a. Smoke flow visualization

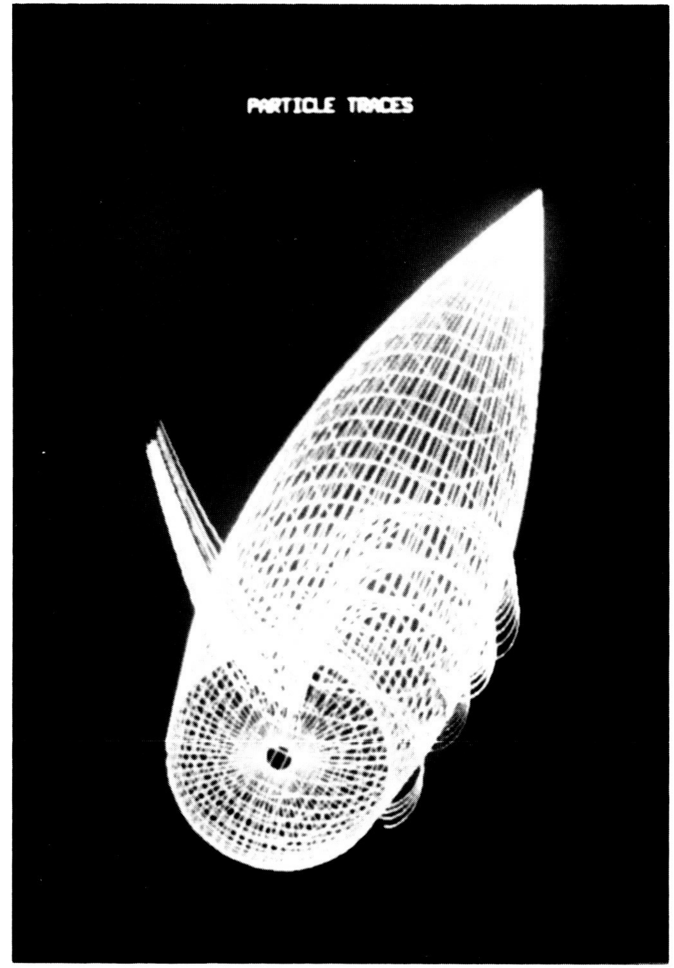

Fig. 7b. 3-D Navier-Stokes computation

3. CURRENT AND FUTURE RESEARCH

Future research plans for five projects on vortex flows, three experimental and two computational, are described in this section.

The time development of the flow past an impulsively started circular cylinder can be related to the spatial development of the steady flow past a pointed axisymmetric body at moderate angles of attack. This analogy has motivated a number of researchers in this Branch to carry out computational studies of the circular cylinder flow. To provide verification of the computational results an experimental flow visualization study of the flow past an impulsively started circular cylinder is being conducted. The study is being carried out in a towing water tank. Photographs of the instantaneous streamline patterns at various points in time during the flow development are being produced.

Apart from vortex/shear layer interactions, another type of vortical flow which is also gaining importance in modern aerodynamics is the interaction between a vortex and another vortical system. For example, a wing wake is often forced to roll up into discrete vortical structures by vertical vibration of the wing, caused by flutter. A longitudinal vortex shed from a strake, with its axis almost perpendicular to these vortices, would then interact with this wake flow. The shed vortex will also interact with the wing tip vortex system. A simplified version of this interaction has been designed where a longitudinal vortex shed from a half-delta wing interacts with spanwise vortices generated in a forced mixing layer. The interest is in studying changes in the two vortical systems induced by the interaction so that the flow field, and hence the effects on aircraft performance, may eventually be predicted.

The flow in a wing/body junction is dominated by a skew-induced secondary flow. The body boundary layer is skewed by the wing, which results in a horseshoe vortex wrapping around the wing. The mechanism does not rely on viscous or turbulent stresses and is therefore found in both laminar and turbulent flows. This type of secondary flow is often encountered in practice (in wing/fuselage or blade/hub junctions, for example), and has provided a significant challenge to the predictor. Some experiments are being designed in which the flow in the junction between a wind tunnel floor and a finite-chord wing will be investigated. Of particular interest are the effects of parameters such as the approach boundary layer properties and wing angle of attack on the flow in and downstream of the wing/body junction.

One of the objectives of the experimental work described above is to obtain Reynolds shear and normal stress data which will lead to a greater understanding of the flow processes and hence to improved turbulence modeling. The present computational effort is intended as a companion to the vortex/mixing layer experiments, in that various modeling concepts will be tried and the numerical results compared with the test data. The computational effort is proceeding along three main avenues. First, advantage is taken of the (practically) zero streamwise pressure gradient to develop a fast and relatively simple streamwise marching code. So far, this code has been employed to develop an algebraic turbulence model for the mixing layer in which account is taken of the velocity defect from the merging splitter-plate boundary layers. Concurrently, a time-accurate Navier-Stokes code is being developed to calculate the time-averaged turbulence quantities from first principles. Interaction of a vortex with the mixing layer will be calculated with a turbulence model employed in a 3-D incompressible Reynolds-averaged code.

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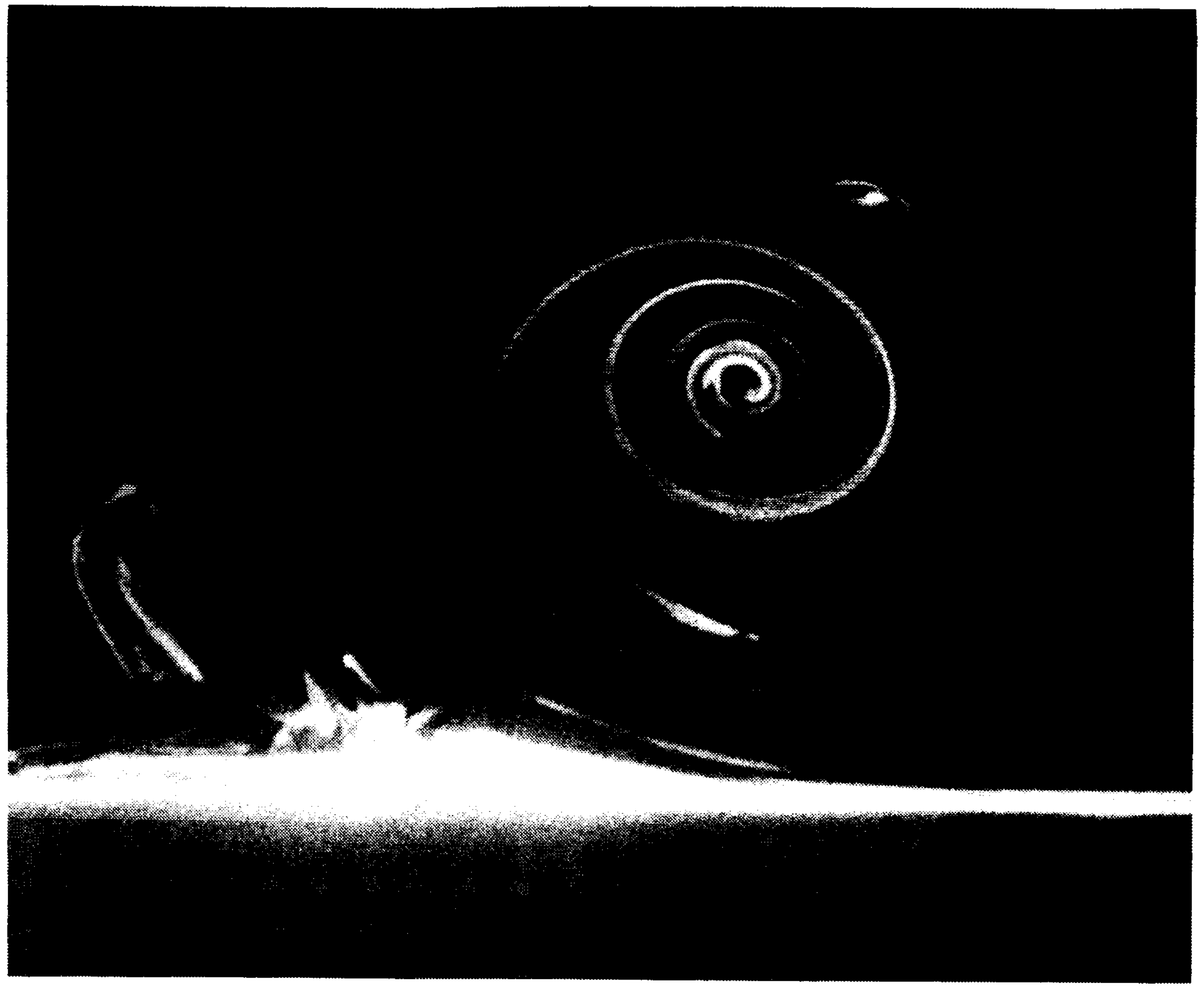
APPENDIX

OPERATING PARAMETERS AND PROPOSED CLASSIFICATION

Table A1. OPERATING PARAMETERS AND CLASSIFICATION

EXPERIMENTAL VALUES						FULL-SCALE VALUES			
EXAMPLE	LENGTH SCALE (L), cm	REYNOLDS NUMBER $(UL/\nu) \times 10^6$	VORTEX Re (Γ/ν)	NON-DIMEN. CIRCULATION, (Γ/UL)	CLASSIFI-CATION (FIG. A1)	LENGTH SCALE (L), cm	REYNOLDS NUMBER $(UL/\nu) \times 10^6$	VORTEX Re (Γ/ν)	NON-DIMEN. CIRCULATION, (Γ/UL)
(a) VORTEX/ SEPARATED B-L.	BUMP CHORD = 20	2.5	62,500	0.025	Id IIb,c				
(b) VORTEX/WING	WING CHORD = 15	0.05	1,550	0.031	Id IIb,c,d	HELICOPTER BLADE CHORD = 46	5.0	1×10^6	0.2
(c) DOUBLE BRANCHED V.G.	WING CHORD = 15	0.13	10,600	0.082	Id				
(d) VORTEX/ MIXING LAYER	TOTAL B-L θ = 0.15	0.0011	1,440	1.26	Id IIb,c				
(e) VORTEX/ BOUNDARY LAYER	B-L θ = 0.11-0.47	0.002-0.0085	10,000	1.2-5.0	Id IIb,c	B-L θ (B747) = 3.0	0.05	50,000	1.0
(f) VORTEX "MEANDER"	B-L θ = 0.11-0.47	0.002-0.007	8,000	1.5-6.25	Id IIb,c				
(g) OGIVE CYLINDER	CYLINDER DIAMETER = 6.6	0.001-0.01	520-5,000	0.5-7.5	Id IIa,b,d	CYLINDER MEAN DIAMETER = 20.0-45.0	1.0-10.0	20,000	5.0



PROPOSED CLASSIFICATION SCHEME FOR VORTEX FLOWS

I VORTEX FORMATION/STRUCTURE

(a) Skew-Induced:
- wing-body juncture ("horseshoe")
- due to "S" bends, in nozzles
- jets/wakes in crossflow

(b) Reynolds Stress-Induced:
- corner flow
- three-dimensional boundary layers

(c) Instability-Generated:
- Taylor-Gortler (concave surface)

(d) Due to Lift:
- finite wing
- delta wing

II VORTEX EVOLUTION/INTERACTION

(a) With Other Vortices:
- perpendicular
- multiple co/counter-rotating

(b) In the Presence of other Mean Flow Perturbation:
- shear
- pressure gradient

(c) In the Presence of Turbulent Flows:
- boundary layer
- mixing layer
- corner flow
- wake

(d) In the Presence of Bodies:
- vortex/wing interaction
- surface proximity
- vortex/fuselage interaction

Figure A1.

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16. Abstract

This report summarizes the research interests of the staff of the Fluid Dynamics Research Branch in the general area of vortex flows. A major factor in the development of enhanced maneuverability and reduced drag by aerodynamic means is the use of effective vortex control devices. The key to control is the use of emerging computational tools for predicting viscous fluid flow in close coordination with fundamental experiments. In fact, the extremely complex flow fields resulting from numerical solutions to boundary value problems based on the Navier-Stokes equations requires an intimate relationship between computation and experiment. The field of vortex flows is important in so many practical areas that a concerted effort in this area is well justified. A brief background of the research activity undertaken is presented in this note, including a proposed classification of the research areas. The classification makes a distinction between issues related to vortex formation and structure, and work on vortex interactions and evolution. Examples of current research results are provided, along with references where available. Based upon the current status of research and planning, speculation on future research directions of the group is also given.

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