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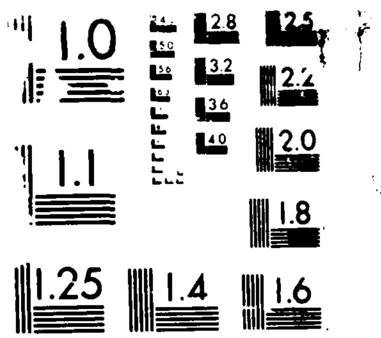

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An elliptic ~~nozzel~~ was found effective for entrainment in jets. It was found that the onset of the fine scale turbulence alters the characteristics of the vortex merging. These studies encompassed plane jets, plunging airfoils, elliptic jets with mass entrainment and impinging jets. Additionally, the 3-D vortical flow over a backward facing step was investigated. A second aspect of the project focused on the emulation of turbulent wall eddy structures, bursting processes and associated turbulent spots. These studies were expanded to encompass the effects of unsteady flow on the turbulent wall structure.

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Final Technical Report

for

AFOSR Contract F-49620-82-K-0019

April 1, 1982 - March 31, 1985

on

UNSTEADY SHEAR LAYERS

by

Ho Chih-Ming - Part 1

Ron F. Blackwelder and Richard E. Kaplan - Part 2

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FINAL TECHANICAL REPORT

FOR

AFOSR CONTRACT F-49620-82-K-0019

APRIL 1, 1982 - MARCH 31, 1985

BY

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I: INTRODUCTION

The research supported by the present contract (F-49620-82-k-0019) are focused in two areas; unsteady separation and jets.

Separation is inevitable in most practical flows and usually is undesirable due to adverse effects on performance. However, extra lift can be produced by unsteady separation on an airfoil under manuvering. Due to difficulties both in experimental techniques and in theoretical analyses, the mechanism of unsteady separation has not been understood. We investigated several separated flow configurations which have led to clarify some fundamental issues about unsteady separated flow and its influence on the lifting surface.

Jets are commonly found in aerodynamic devices, e.g., jet engines, ejectors, ram jets, etc. One of the main issues is the enhancement of entrainment. We have found a simple and extremely efficient way, an elliptic nozzle, to increase the entrainment by an order of magnitude. Another aspect of jet research is to examine the roll of small eddies in jets. The engulfing of surrounding fluid into the jet is mostly accomplished by the evolution of large scale structures. Fine scale mixing relies on the small turbulent eddies. In a plane jet, we examined the generation process of the small eddies in detail. Most importantly, we found that the onset of the fine scale turbulence alters the characteristics of the vortex merging. In other words, Reynolds number effects on large scale structures are not minimal. This point has been neglected in the past studies on coherent structures.

Brief summaries of all these projects are provided here. Detailed reports can be found in published papers or in Ph.D. theses.

II: INTERACTION BETWEEN SMALL SCALE EDDIES AND LARGE COHERENT STRUCTURES IN A PLANE JET

The preferred mode in a jet increases its value with jet exit speed in the low velocity range. After reaching a critical speed, the preferred mode reaches a constant value . In the present study, we show that a change of characteristics of the preferred mode is caused by the small scale transition which occur near the critical speed (Fig.1). The vorticity distribution of the large coherent structure is much diffused after the transition (Fig.2) and hence, the vortex merging is very much reduced (Fig.3). In other words, small scale turbulence can strongly affect the evolution of large coherent structures. For the first time, this finding shows that the Reyrolds number has strong effect on coherent structures.

III: UNSTEADY AERODYNAMICS OF A PLUNGING AIRFOIL

When an airfoil in plunging motion with a mean angle of attack is at its static stall angle, the maximum lift is about two times higher than the maximum static lift(Fig. 4). The dynamic stall happens when the airfoil is at the lowest position. The moment is positive (Fig. 5) which is opposite to the case for a pitching airfoil. Therefore, The unstady aerodynamic properties critically depend on the mode of motion. The positive moment is generated by a trailing edge stall which produces suction on the lower surface and pressure on the upper surface (Fig.6).

When the mean angle of attack was set far below the static stall angle, no globle separation occurs on the airfoil. We found that the classical Theodorsen theory can reasonably predict the aerodynamic properties even for a reduced frequency close to one. The Kutta condition was investigated both from the curvature of the stagnation streamline and the trailing edge loading. The unsteady Kutta condition for a plunging airfoil holds for reduced frequency less than 0.5.

IV: MASS ENTRAINMENT AND VORTEX INDUCTION IN AN ELLIPTIC JET

In a small aspect ratio (AR = 2:1) elliptic jet, the mass entrainment was found about one order of magnitude higher than that of a circular jet (AR = 1:1) or a plane jet (AR = 24:1). From this study, we have identified a new class of mass entrainment mechanism - self induction of coherent structures. Due to the self induction of vorticity distributed on an asymmetric contour, the elliptic vortex experiences axis switching while it convects downstream. The portion of the vortex near the minor axis moves outward and therefore large amount of ambient fluid is induced into the jet.

V: UNSTEADY SEPARATION IN AN IMPINGING JET

When the coherent structure in an impinging jet approaches the wall, it induces an unsteady adverse gradient which retards the flow in the viscous region. At the same time the coherent structure brings high speed fluid toward the inviscid region just above the retarded flow region. A local shear layer is therefore generated at the inviscid-viscous interface. Thus, the unstable shear layer initiates the unsteady separation. The new perspective of looking at unsteady separation from the shear layer point of view could lead to many aspects of controlling the separated flows.

VI: SEPARATED ZONE OF A 3-D BACKWARD FACING STEP

A backward facing step is a generic model of many practical flows, e.g., ram jet, flame holder in a combustion chamber etc. All these configurations are 3-D in nature, but laboratory studies are limited to 2-D. In the present investigation, we have examined the separation bubble in a backward facing step with a 1:1 aspect ratio. The reattachment length is only about 4 step depths which is much shorter than that in a 2-D case. The reattachment line shows a highly 3-D feature. The survey of all three velocity components by LDV indicates that two stationary vortices exit in the separated region. The resultant downward flow in the center span make the reattachment length much shorter than that off center. The dominant time scale in the separated zone is about two orders of magnitude lower than that in the free shear layer. The vortices in the shear layer are 3-D also and are not sensitive to 2-D forcing.

VII: UNSTEADY SEPARATION AND ITS MANIPULATION ON LIFTING SURFACES

An unsteady water channel was designed and built to study the possibility of manipulating the aerodynamic properties of an unsteady airfoil. The channel provides varieties of unsteady flow conditions. The flow field will be mapped by LDV and instantaneous force measurements are obtained by 2-D drag cells. At present most of the components are in working condition. Tests will start in the near future.

VIII: PATENT AWARD

"MIXING APPARATUS USING A NONCIRCULAR JET OF SMALL ASPECT RATIO" United States Patent Number 4519432.

IX: INVITED TALKS

1. "Fundamental Aspects of Unsteady Separation", AFOSR Super Maneuverability Initiative Meeting, Boulder, March 11, 1985.

2. "The Control of Entrainment in Mixing Layers", ASME Applied Mechanics Division Summer Meeting, San Antonio, June 17-21, 1984.

3. "On the Experimental Studies of Unsteady Separation", International Symposium on Recent Advances in Aerodynamics and Aeroacoustics, Stanford University, August 22-26, 1983.

X: PUBLICATIONS

1. "Dynamics of an Impinging Jet: Part 2; The Noise Generation", with Nosseir N.S.M., Journal of Fluid Mechanics, Vol. 116, p. 379-391, 1982.

2. "Visualization of an Elliptical Jet", with Gutmark, E., Bulletin of the American Physical Society, Vol. 27, p. 1183, 1982.

3. "Development of an Elliptical Jet", with Gutmark, E., Bulletin of the American Physical Society, Vol. 27, p. 1184, 1982.

4. "Evolution of Coherent Structures in a Lip Jet", with Hsiao, F.B., Structure of Complex Turbulent Shear Flow, p. 121-136, Springer-Berlin, 1982.

5. "Preferred Modes and the Spreading Rates of Jets", with Gutmark, E., Physics of Fluids, Vol. 26, p. 2932-2938, 1983.

6. "An Alternative Look at the Unsteady Separation Phenomenon", International Symposium on Recent Advances in Aerodynamics and Aeroacoustics, invited paper, 1983.

7. "Visualization Study of a 2-D Jet", with Hsiao, F.B., Bulletin of the American Physical Society, Vol. 28, p.1354, 1983.

8. "On the Forced Elliptic Jet", with Gutmark, E., International Symposium on Turbulent Shear Flows, 1983.

9. "Genesis of Unsteady Separation", Symposium on Unsteady Separated Flow, p. 165-168, 1983.

10. "On Sinuous Mode and Varicose Mode in a 2-D Jet", with Hsiao, F.B., Bulletin of the American Physical Society, Vol. 29, p. 1519, 1984.

11. "Perturbed Free Shear Layer", with Huerre, P., Ann. Rev. of Fluid Mech., Vol. 16, p. 365-424, 1984.

12. "Unsteady Separation in a Boundary Layer Produced by an Impinging Jet", with Didden, N., accepted by Journal of Fluid Mechanics, 1984.

13. "Near Field Pressure Fluctuations of an Elliptical Jet", with Gutmark, E., AIAA Journal, Vol. 23, p. 354-358, 1985.

14. "Vortex Induction and Mass Entrainment in a Small Aspect Ratio Elliptic Jet", with Gutmark, E., submitted to Journal of Fluid Mechanics, 1985.

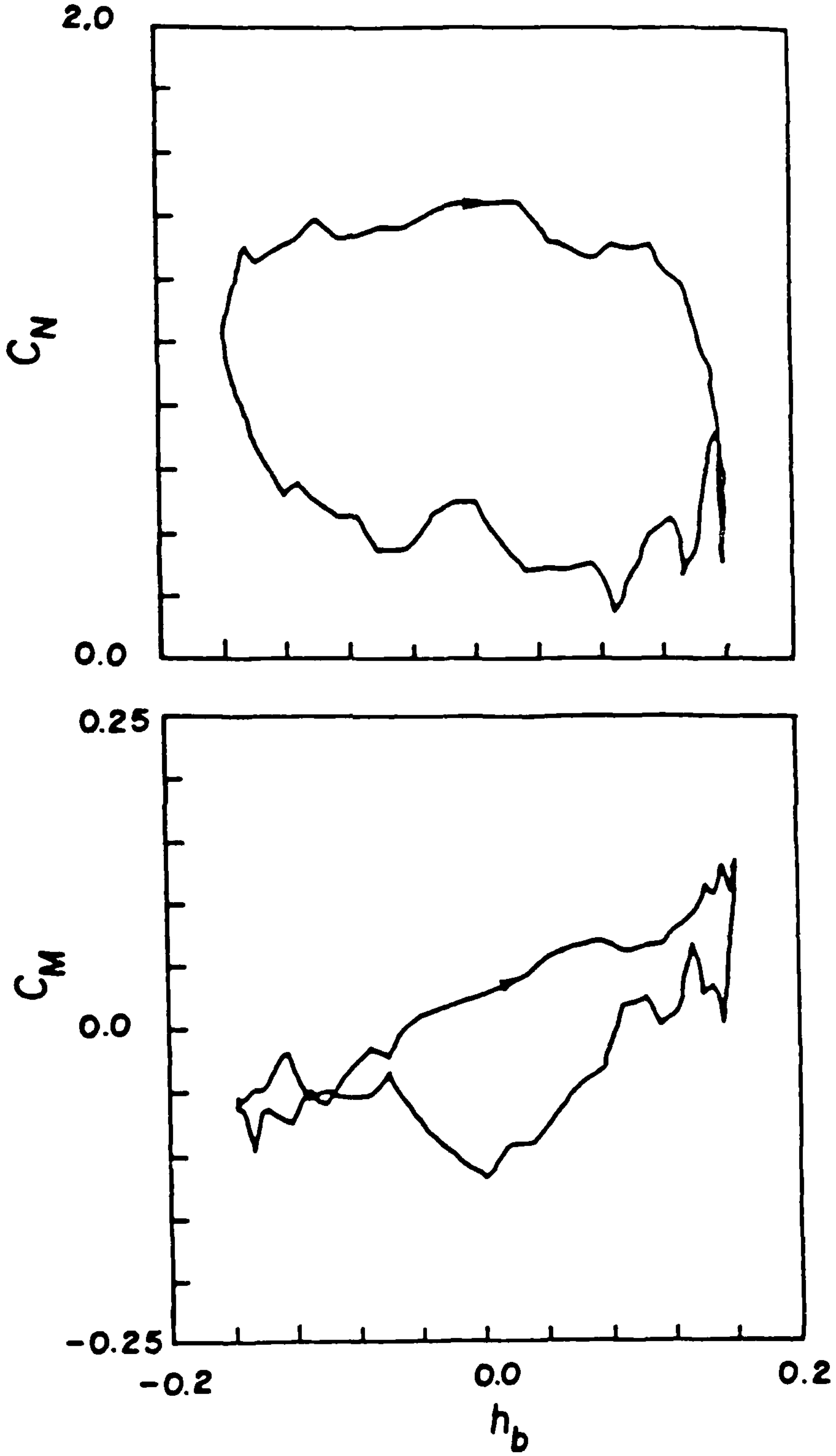

FIG: 1

FIG: 2

Normal Force and Pitching Moment Coefficient loops for h_b = 0.16, k = 0.89, $\alpha_e = 12° + 8.2° \cos(\omega t)$

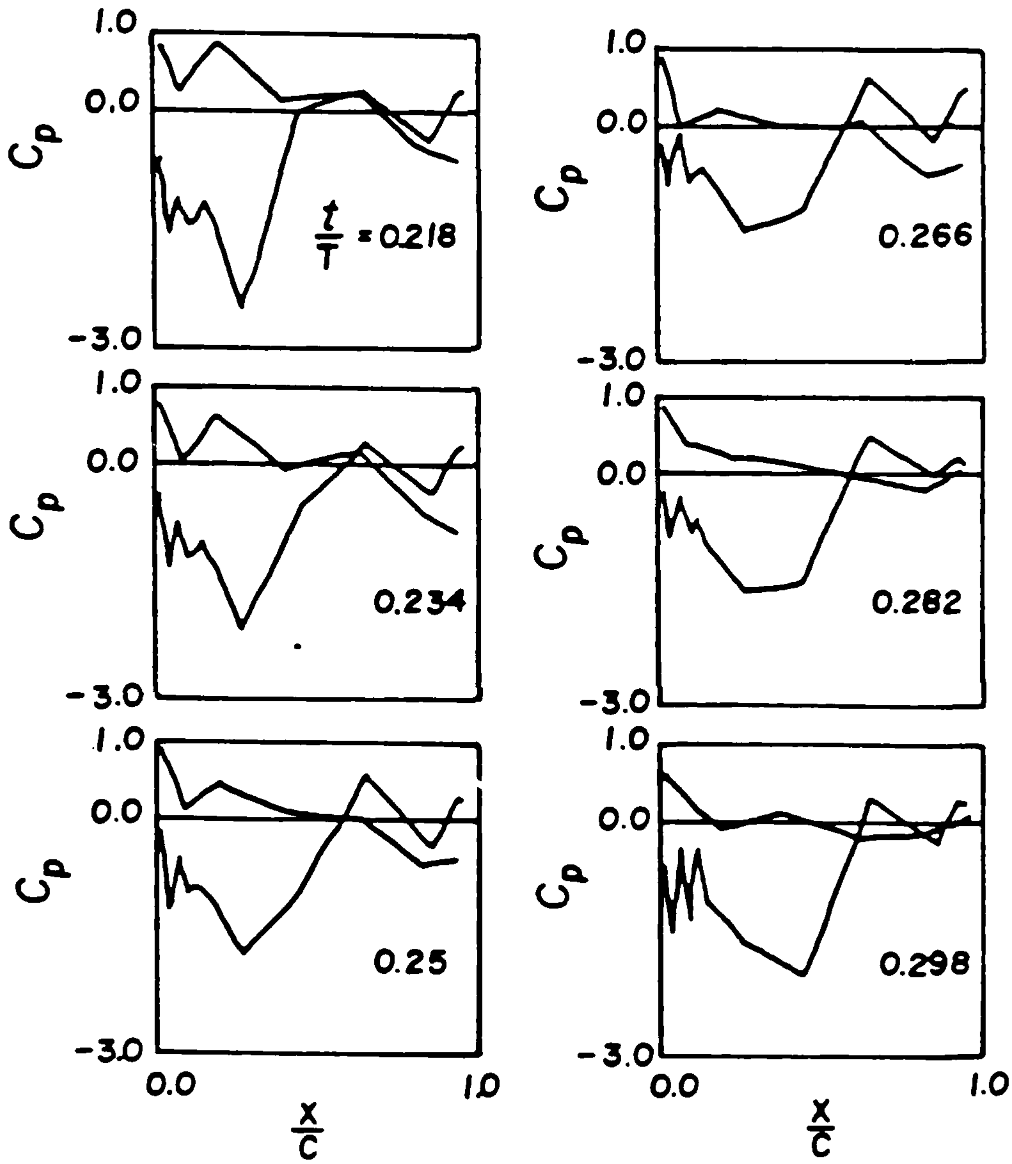

FIG: 3

Chordwise Distribution of Pressure
Coefficients for h_b=0.16,
k=0.89, α_e=12° + 8.2°cos(ωt)

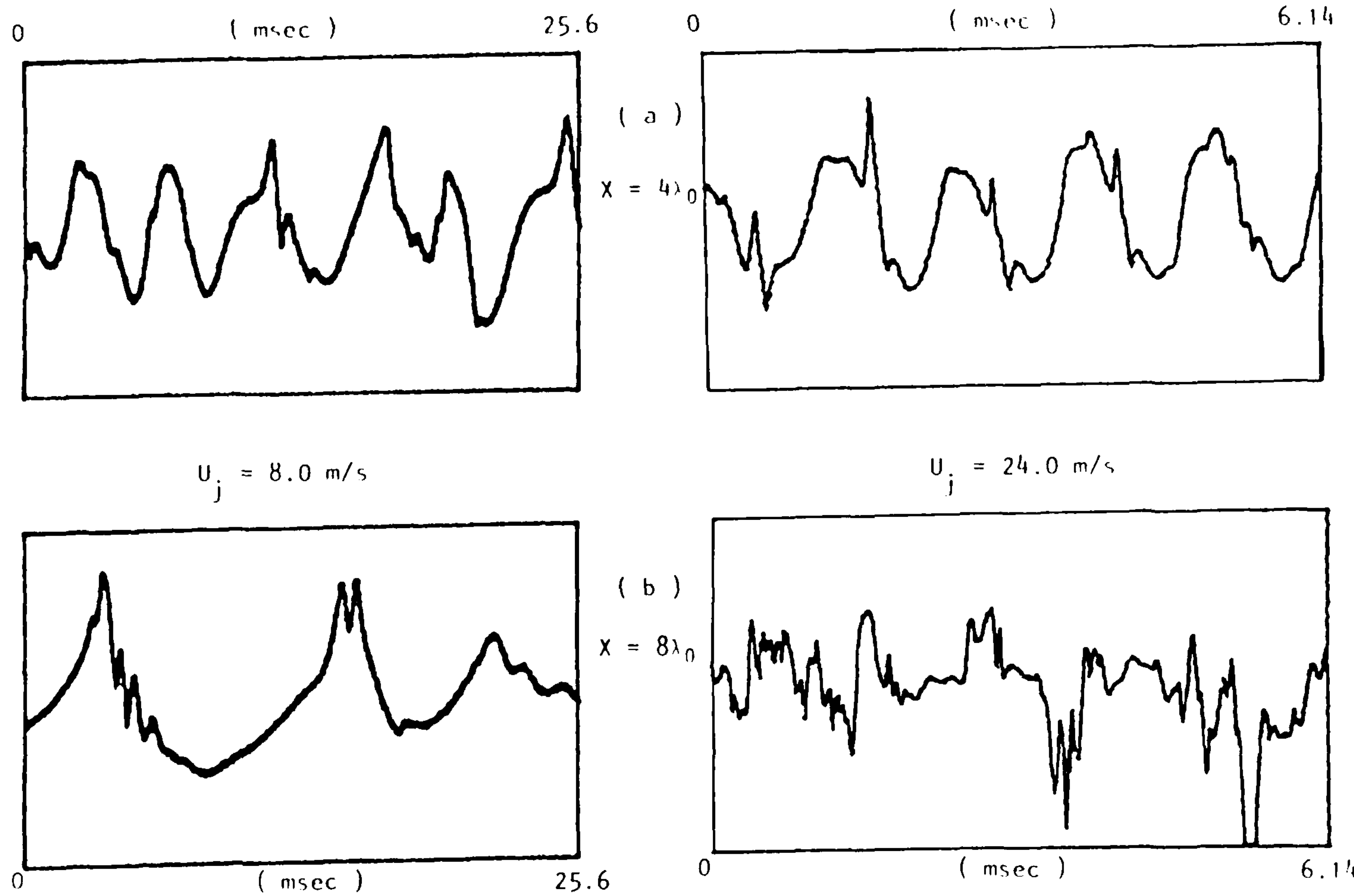

Figure 4 : Time traces of streamwise velocity fluctuations at the transverse station where $U = 0.5U_j$.

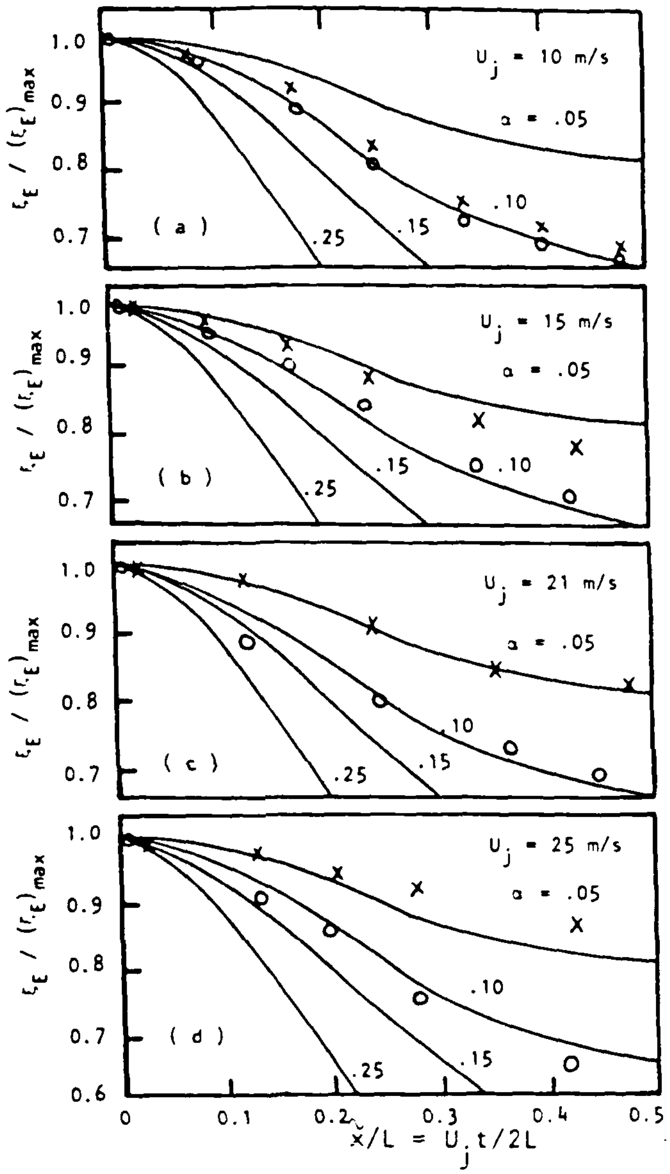

FIG: 5

Ensemble averaged vorticity distributions of the preferred mode compared with the Stuart's [42] theoretical vorticity function for different velocities: (a) 10 m/s, (b) 15 m/s, (c) 21 m/s, (d) 25 m/s. x -- Non-merging vortices; o -- merging vortices. The data are obtained before the vortex merging location, closest to the end of the potential core. L = twice the vorticity thickness.

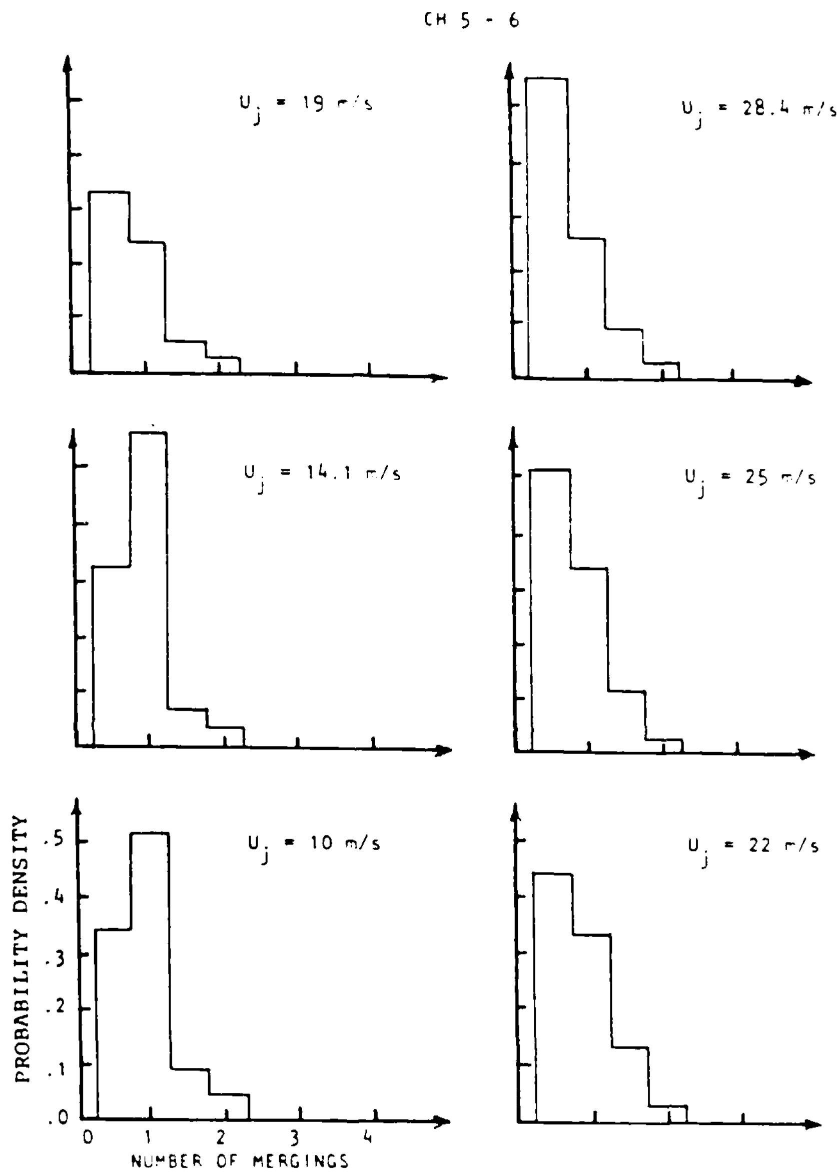

FIG: 6

Histograms of the number of vortex mergings of the preferred mode between Ch 5 & Ch 6 with jet exit velocity.

FINAL TECHNICAL REPORT

FOR

AFOSR CONTRACT F-49620-82-K-0019

April 1, 1982 - March 1, 1985

by
Ron F. Blackwelder
and
Richard E. Kaplan

RESEARCH

The research performed under the above contract consists of the following main topics:

I Emulation of Turbulent Wall Eddy Structures

The growth, breakdown, and transition to turbulence of counter-rotating streamwise vortices, generated via a Görtler instability mechanism, was used to experimentally model the eddy structures found in transitional and turbulent flat plate boundary layers. The naturally occurring vortices have been studied using smoke-wire visualization and multiple probe hot-wire rakes. Results show that the vortices form low speed regions between them as low momentum fluid is pumped away from the wall. The low seed regions grow downstream in the normal direction faster than a nominally Blasius boundary layer creating strongly inflectional normal and spanwise profiles of the streamwise velocity component. Instability oscillations develop on these unstable profiles of which scale with the local shear layer thickness and velocity difference. Contrary to expectations however, the spatial scales of the fluctuations correlate more with the velocity gradient in the spanwise direction rather than the normal velocity gradient. The nonlinear growth of the oscillations is quite rapid and breakdown into turbulence occurs within a short time scale.

II Bursting Process in Turbulent Boundary Layers

The bursting frequency in turbulent boundary layers was measured over the Reynolds-number range $10^3 < U_\infty \Theta/\nu < 10^4$. When scaled with the variables appropriate for the wall region, the non-dimensional frequency was constant independent of Reynolds number. A strong effect of the sensor size was noted on the measured bursting frequency. Only sensors having a spatial scale less than twenty viscous lengthscales were free from spatial-averaging effects and yielded consistent results. The spatial-resolution problem was apparently the reason for erroneous results reported in the past.

Instantaneous velocity signals were measured simultaneously at several spanwise and normal locations to compute the velocity gradients in the wall region. Inflectional profiles were found on a regular basis in both directions which were capable of supporting growing disturbances. Surprisingly, the spanwise velocity gradients attained larger magnitudes and occurred more frequently than those in the normal direction. This information will be extremely useful in guiding efforts to control the turbulence in the wall region and may explain why riblets and grooves have been able to reduce the drag in turbulent boundary layers.

III Structure of a Turbulent Spot

Mini-thermocouples having a rapid time response were developed and used to study an artificially generated turbulent spot in a heated boundary layer The simultaneous temperature traces were used to determine the spots's leading and trailing edge characteristics and were ensemble averaged. The measurements on the centerline of the plate used a constant velocity and variable streamwise positions providing a Re_x range of 2.45 to 12.6 x 10^5. At one axial position the effect of free stream velocity variation was studied and off-axis measurements were obtained.

The shape of the interface between the laminar flow and the spot turbulent flow was described by conventional and conditional histograms The length of the spot's leading edge front (i.e. the "overhang") increased linearly with the downstream distance. Off-axis, the length of the overhang decreased slightly towards the "wing tips" and became large with respect to the spot's streamwise extent. The trailing edge changed less significantly in the downstream direction.

It was shown that two consecutive spots might have an effect on one another if the trailing spot is in the calmed region of the first one, especially, by reducing the celerity of the second spot's leading edge.

IV Effects of Unsteady Flow on the Turbulent Wall Structure

Experimental results obtained in a turbulent channel flow undergoing forced oscillations of 10-70% of the centerline velocity were obtained. The mean velocity and the streamwise turbulent intensity of the parallel channel flow are uneffected by the large amplitude oscillations. At high frequencies, the vortical diffusion from the boundary is contained within the viscous wall region. In this frequency range, the periodic flow field is best described by Stokes solution for flow over an oscillating wall. The amplitude and phase are correlated by the Stokes length scale, ℓ_s, made nondimensional by the viscous length scale, ν/u_τ. The wall shear stress was measured while the Reynolds number, amplitude and frequency were varied systematically. For $\ell_s < 10\nu/u_\tau$ the oscillating shear stress amplitude increased above the Stokes value and the phase lead was zero. The amplitude and phase of the modulated turbulent shear stress were also measured.

V Visitation of European Laboratories

Several European laboratories were visited by Dr. Blackwelder during his sabbatical leave from USC. Most of these labs were involved in research on different aspects of unsteady fluid mechanics. A short report was forwarded to the Air Force Office of Scientific Research at the conclusion of his sabbatical and is included here for completeness as Appendix A.

PUBLICATIONS

1. "The Bursting Frequency in Turbulent Boundary Layers", R.F. Blackwelder and J.H. Haritonidis, J. Fluid Mech., 132, 87, 1983.

2. "Breakdown of Streamwise Vortices near a Wall", J.D. Swearingen and R.F. Blackwelder, Structure of Complex Turbulent Shear Flows, Ed. R. Dunes and L. Fulachier, Springer-Verlag, 1983.

3. "Analogies between Transitional and Turbulent Boundary Layers", R.F. Blackwelder, Physics of Fluids, 26, 2807, 1983.

4. "Parameters Controlling the Spacing of Streamwise Vortices on Concave Walls", J.D. Swearingen, AIAA-83-0380, 1983.

5. "The Breakdown of Streamwise Vortices Embedded in a Laminar Boundary Layer", J.D. Swearingen and R.F. Blackwelder, Bull. Am. Phys. Soc., 28, 1387, 1983.

6. "Decreasing the Side Wall Contamination in Wind Tunnels", T. Motihashi and R.F. Blackwelder, J. Fluids Engineering, 105, 435, 1983.

7. "Wave Packets and Pulse Disturbances from a Slit in Flat Plate Laminar Boundary Layers", J. Tso, R.F. BLackwelder, and R.E. Kaplan, Bull. Am. Phys. Soc., 29, 1555, 1984.

8. "Instantaneous Streamwise Velocity Gradients in the Wall Region", J.D. Swearingen and R.F. Blackwelder, Bull. Am. Phys. Soc., 29, 1528, 1984.

9. "Experimental Study of Unsteady Turbulent Boundary Layers under Positive and Zero Pressure Gradients", G. Binder, S. Tardu, R.F. Blackwelder and J.L. Kuny, AGARD CP 386, p 10, 1985.

10. "Large Amplitude Periodic Oscillations in the Wall Region of a Turbulent Channel Flow", G. Binder, S. Tardu, R.F. Blackwelder and J.L. Kuny, Fifth Symposium on Turbulent Shear Flows, Springer-Verlag, 1985.

11. "On the Structure of a Turbulent Spot in a Heated Laminar Boundary Layer", E. Gutmark and R.F. Blackwelder, submitted to Experiments in Fluids.

INVITED TALKS

1. "Simulation of the Turbulent Bursting Process using Wall Curvature", IUTAM Symposium on Structure of Complex Turbulent Flows, Marseille, August, 1982.

2. "Breakdown of Streamwise Vortices near a Wall", Drag Reduction Symposium, National Academy of Science, Washington, September, 1982.

3. "Eddy Detection, the Bursting Phenomenon and Large Scale Motion in Turbulent Boundary Layers", at the Von Karman Institute for Fluid Dynamics, Brussels, Belgium, March, 1983.

4. "Eddy Structure in Turbulent Boundary Layers", Symposium on Chaos and Large Scale Structure in Turbulence, National Research Council, Santa Barbara, CA, October, 1982.

AWARDS AND PATENTS

- o Fulbright Grant and Professor Associe, Institut National Polytechnique de Grenoble, France

- o Lift Control Device for Delta Wings - Patent Pending

APPENDIX A

Institut de Mecanique des Fluides de Marseille
l'Universite d'Aix-Marseille II
1 rue Honnorat
13003 Marseille

The Honnorat laboratory near the Gare St. Charles has fluid mechanics research primarily in supersonic and unsteady subsonic flow fields. C. Maresca, D. Favier and C. Barbi have conducted and are continuing several experiments studying enhanced lift due to unsteady motion, unsteady separation and vortex interaction with rotating blades. They seem to be closely tied to basic problems in the French aircraft and helicopter industry.

Favier completed his thesis in 1980 on the unsteady motion of an airfoil at high angles of attack with sinusoid motion; 1) parallel and 2) perpendicular to the mean flow. He found greater lift enhancement in the first mode. The second type of motion produced results similar to those in a pitching mode. Since 1980 he has combined both types of unsteady motion to simulate a simultaneous oscillation of the free stream velocity and angle of attack both in the in-phase and out-of-phase modes. The enhanced lift due to the two motions is additive in a non-linear manner depending upon the phase. For example, an instantaneous lift coefficient of approximately 6.0 is obtained when the variations are in phase. Presently Favier is studying the effects of an unsteady dynamic stall vortex shed from an upstream oscillating airfoil on a downstream airfoil. He finds the lift of the stationary airfoil is enhanced whenever the vortex passes over its suction surface.

Barbi earlier worked on the unsteady motion of a circular cylinder oscillating papallel and perpendicular to the free stream. He is now preparing an experiment to examine the details of unsteady separation to study the criteria for separation in an unsteady flow.

Maresca is presently mapping out the trajectory of wingtip vortices produced from a model helicopter in hover to aid in developing better numerical predictions of the vortical dynamics. He is conducting an experiment using LDV to measure the circulation around a rotor blade of a helicopter. His measurements do not agree with the equation $L = \rho U_\infty \Gamma$ on a 3-D airfoil and he is presently seeking an explanation including the idea that some circulation is continuously "shed" by the airfoil. In the future he plans to investigate the interaction of a wingtip vortex on a stationary and/or oscillating airfoil downstream.

O.N.E.R.A.
Centre d'Etudes et de Recherches de Toulouse
2, avenue Edouard Belin
31055 Toulouse Cedex

Although this laboratory has been very active in research on unsteady boundary layers in the past, ONERA has stopped funding this basic research, so at present no experiments on unsteady flows are being conducted. J. Cousteix and R. Houdeville will begin a new experiment in summer '84 on the effects of an oscillating flap on the global properties of an airfoil. A 20 cm chord airfoil with oscillations up to 100 Hz in a 20 m/sec air stream will be used to experimentally model existing devices on military aircraft. Numerical modelling of unsteady flows is continuing by adjusting codes to predict data from other laboratories.

Other stationary low speed phenomena being studied includes an experimental and analytical exploration of the cross flow instability occurring on a highly swept wing, development of skin friction gauges with high frequency response and an experimental study of the interaction of a wake of a wing with a boundary layer on a fuselage.

Office National d'Etudes et de Recherches Aerospatiales
Headerquarters and Laboratories at Chatillon &
Research Wind Tunnels at Chalais-Mendon

These two main branches of ONERA re presently only working on two projects involving unsteady aerodynamics. The first is a more fundamental study of an airfoil oscillating in pitch at low angles of attack, i.e., below stall. The second is an investigation of the interactions of helicopter blades and their wakes. Both of these studies are being conducted by Werle and are visualization with no probe measurements. Another study which was recently completed examined the flow field over an airfoil with an oscillating flap at large angle. By oscillating the flap, the flow field remained attached over 10-50% of the cycle and presumably created a larger average lift coefficient. This configuration may have several advantages over pitching the entire airfoil; namely the structural loading problems may be less severe and a higher average lift may be attained. This investigation at Chatillon was by visual methods and has been terminated, however further work on this problem is to be pursued at ONERA in Toulouse using probe techniques.

The other research at these two locations is primarily aimed toward numerical simulation and computation following three avenues; 1) modelling using k-ϵ and algebraic stress equations, 2) large eddy simulation and 3) direct solution of the Navier-Stokes equations. Velocity and pressure data on an ellipsoidal cylinder with a 30 cm x 90 cm cross section are being gathered at Re $\sim 10^7$ and angles of attack up to 40° to provide data for turbulence models in a separated flow field. Transonic shock wave interaction with boundary layers have been studied experimentally and are being modelled numerically. Considerable effort is being devoted toward large eddy simulation similar to the work at AMES, however different sub-grid scale models are being tested. Much of the present work models homogeneous turbulence with plane strain or rotation at modest Reynolds numbers. Experimental work on homogeneous turbulence with rotation and rotation is being planned at ONERA. Clearly they are developing an expertise and methodology similar to that at NASA Ames.

Institute de Mecanique
Universite de Grenoble
Grenoble, France

In addition to the ONERA and Marseille groups, this laboratory has been one of the most active in France for studying the fundamental aspects of unsteady flow. Most of the work has been under the direction of G. Binder. He and Favre-Marnier applied a small amplitude oscillation perpendicular to the mean flow at the exit of a high aspect ratio 2-D jet. They found that the mixing and spreading rate of the jet could be significantly increased (i.e. by factors of 3 to 10) depending upon the frequency of the disturbance. A rounded lip instead of a sharp edged exit on the jet was able to make use of the Coanda effect to enhance the flapping angle ıd hence the mixing. A similar study is presently being pursued in an axisymmetrical jet.

Binder and his colleagues have also studied an unsteady fully developed channel flow. They were the first to show that a Stokes layer can exist in the near wall region of the turbulent flow if the frequency is sufficiently high that the Stokes thickness is less than approximately 10 ν/U_τ. When the amplitude is sufficiently large, they have observed a thin region of reverse flow near the wall during part of the cycle even though the mean flow is always downstream.

Centre d'Etudes Aerodynamique & Thermique
Universite de Poitiers
43 rue de l'Aerodrome
Poitiers 86000

This laboratory, under the direction of Professor Alziary de Roquefort, is working on a broad variety of basic and ar)lied fluid mechanical problems. Research involving unsteady flow include:

1) An experimental study of a turbulent boundary layer with emphasis on the wall region by J. Tartarin. This work (reported in the Revue Phys. Appl. 18, p. 495, 1983) has been terminated primarily because the test facility had a limited frequency and amplitude range and possibly other problems leading to harmonic distortion. The data reported in the above reference seemed to agree best with with those of Acharya and Reynolds, whose results are known to be contaminated by vibration.

2) An investigation of the validity of the unsteady Kutta condition in unsteady flows by Ardonceau. He has measured the amplitude and phase of the pressure on a pitching airfoil (unfortunately he was ill during my visit; thus I was unable to discuss his results).

   He plans to continue this work by flying a model in the atmosphere in addition to wind tunnel tests.

Other unsteady flow phenomenon of less interest to aerodynamicists includes; 1) the study of the imposed pressures on a building in a gusty environment where the gusts are vortices shed from a pitching airfoil, 2) the velocities in the intake manifold and exhaust of a 4 cylinder automobile engine undertaken for Peugeot and 3) an investigation of keel design for boats operating in a pitching mode imposed by surface waves.

Laboratorie de Mecanique et d'Energetique
Universite de Orleans
45046 Orleans

Although this group has only four or five active researchers, they are devoting considerable effort towards unsteady fluid mechanics. Most all of their work is applied research related to mixing and heat transfer.

Burnel has used an oscillating sonic nozzle in a 9.2 cm diameter pipe to create an oscillating pipe flow. He has measured the streamwise and normal velocity components and the pressure and finds a strong resonance phenomenon in the flow field associated with an "organ pipe" standing wave. Hence, the periodic component of the measured variables has a large streamwise variation in amplitude (typically 20%) even though the mean flow is independent of that direction. Burnel feels that this effect is an important aspect of this flow and has documented it at three harmonic frequencies. Mainardi has used an almost identical experimental facility to study the effect of unsteadiness on more practical problems; e.g. on orifice discharge coefficients, heat transfer, etc. He has also used a crude one-dimensional model to correlate and analyze some of his data. In another experimental investigation, Burnel and his colleagues are using Faraday probes to measure the unsteady flow in the intake manifold and carburetor of an internal combustion engine. They have studied ten different manifolds to determine the effect of length and diameter on the unsteady mixing and overall efficiency of the engine.

One unique steady state flow experiment consisted of measuring the flow field around an elliptical cylinder having a fairing and suction on the downstream face. With small amounts of suction, lift coefficients of 8 and drag coefficients of unity were attained. Two prototypes 12 meters long with 2 meter chords are presently being constructre' to provide propulsion for a boat on a trans-Atlantic voyage.

Queen Mary College
Aeronautics Department
London

Although considerable research in unsteady aerodynamics occurred here in the 1970's under the leadership of Professor A.D. Young, the level of activity has declined considerably since his retirement. The unique open test section wind tunnel used by Patel to study unsteady laminar and turbulent boundary layers is presently being used for undergraduate projects.

An experimental study by Lin Bernstein is using a wind tunnel similar to that of Patel's to induce an oscillatory transverse velocity component into a laminar boundary layer and is measuring the two velocity components parallel to the plate. This project appears to be a low level effort and few results have been obtained.

Institut de Mecanique Statistique de la Turbulence

Universite d'Aix-Marseille II

12, avenue General-Leclerc

13003 Marseille

This laboratory is continuing to devote most of its effort toward understanding classical stationary turbulent flow fields including spectral relationships between velocity and scalar variables, boundary layers subjected to a sudden transverse strain, mixing in asymmetrical wakes, etc. Two research projects that may be of interest to unsteady aerodynamicists are: 1) an attempt by Duma to drastically alter and/or eliminate the wing tip vortex of helicopter rotors by shaping the rotor cross-section to asymptotically decrease the circulation distribution near the rotor's tip and, 2) a preliminary study by Begieur of the unsteady vortex shedding from airfoils in a Darieus wind mill.

Mechanical Engineering Department
University of Manchester
Institute of Science and Technology
Manchester, England

Most of the research on unsteady fluid mechanics in this department concerns injection and spray technology. Alan Yule has been working for several years on developing injectors for diesel engines. Most of his effort is now devoted towards small injectors operating at high pressures for the next generation of automobiles. He has developed a small continuous wind tunnel which operates at 500 atmospheres pressure to study the penetration and dispersion of unsteady jets injected into a cross stream.

Much of the remaining basic research in the department is devoted toward providing heat transfer and fluid dynamical data for the k-ε turbulence model of Brian Launder. Although Professor Launder has thought about modelling unsteady flow fields, he feels that one must first develop a good equation for the length scale before progress can be attained.

Laboratoire de
Mecanique des Fluides
Ecole Centrale
Lyon, France

This laboratory is one of the largest and best recognized fluid mechanics groups in France. Although their research spans a broad spectrum of topics, the only work currently on unsteady flow phenomenon is a study of the internal fluid mechanics in combustion chambers. Initially the unsteady flow without reaction and heat release were studied; at present, combustion is included. The primary interest is to improve the efficiency of the engine by altering the fuels, injection process and geometry of the camber.

Other research at the Laboratoire de Mecanique des Fluides include 1) a large effort devoted to the study of turbo machinery, 2) a new anechoic wind tunnel consisting of a 150 m/sec 20 cm x 40 cm jet exiting into a large anechoic chamber presently being used for adrodynamic noise studies, 3) several researchers working on numerical modelling of turbulence including k-ε models and large eddy simulation, 4) a 7' x 12' environmental wind tunnel for investigating pollutants, cooling towers, etc. and 4) other efforts devoted to basic studies of homogeneous turbulence, two phase flow, etc.

Institut de Mecanique des Fluides de Toulouse
Institut National Polytechnique de Toulouse
2 rue Charles Camichel
31071 Toulouse Cedex

This laboratory has two ongoing research problems remotely related to unsteady flow fields. In the first, P. Chassaing and H. Ha Minh are exploring the rapid changes in the eddy structure of a jet produced by a transitional pipe flow. Visualization using high speed Schlieren photography show a prounounced effect on the jet structure as turbulent puffs exit from the pipe flow. In the second, H. Boisson and others have experimentally studied the natural unsteady shedding of eddies from a circular cylinder and have developed a computer algorithm which incorporates the intermittency factor.

Imperial College
Aeronautics Department
London

There is very little unsteady aerodynamics research at Imperial College, however the bio-mechanics group is actively investigating unsteady flows related to the pulmonary and circulatory systems. One of their more novel projects is an exploration of the trachea in giraffes since the fluid must travel great distances during each cycle.

Peter Bradshaw is continuing his studies of complex turbulent flow fields. He has recently completed an experimental study of three interacting boundary layers near the trailing edge of an airfoil with extended flaps. He is presently studying the interaction of one or two air jets blowing perpendicular into a uniform flow and impinging onto a wall with a fully developed boundary layer. The primary interest is related to the horseshoe vortex formed in the boundary layer around the impinging jet. He has found that below a critical jet momentum threshold, no such vortex is formed. The upwelling region between two impinging jets is also being studied.

Other notes of interest from Imperial are that: 1) P. Bradshaw has altered his view on turbulence modelling and has ceased his numerical endeavor. He feels that a universal model is no longer obtainable and that the Large Eddy Simulation approach of the Stanford and Ames groups will reach a solution sooner than modelling the individual turbulence terms.

2) For a long time, the efforts of the Imperial group have avoided the study of large eddies in shear flows because they felt the large eddies should not be singled out as an important element of the flows. That view

has been altered and several experimental projects are underway using conditional sampling to study the large eddy structure.

3) Peter Bearman and colleagues have begun a large long term project to study automobile aerodynamics funded by Hondo Motor Co. A new wind tunnel with a test section of approximately 8' x 10' will be used to study one-third scale models at realistic Reynolds numbers.

III Physikalisches Institute
der Universität Göttingen
Bürgerstrasse 42
Göttingen, Germany

This Institute is primarily devoted to studies of acoustics and vibrations. Professor Ronneberger is the only person there who has actively worked in unsteady flow fields. He and his students have constructed a channel flow with one oscillating side wall and measured the streamwise velocity component on the fully developed turbulent flow field. He views the unsteadiness as introducing an oscillating Stokes layer into the fluid. At high frequencies, the layer is so thin that it does not interact with the turbulence which has its maximum energy at a location further from the wall. Thus only at low frequencies, where the Stokes layer extends outward into the strongly turbulent regions does he expect an interaction between the unsteadiness and the turbulence. His data tend to support this thesis.

Unfortunately, he has curtailed his research lately because of the lack of funding. He stated that he did not know of any other ongoing research in Germany in unsteady aerodynamics.

Aerodynamische Versuchts Anstalt - DFVLR
Böttingenstrasse 10
Göttingen, Germany

At present there is no research in the AVA on usteady flow fields. However, the group directed by Professor Hornung, i.e. the Institute für Experimental Strömungsforschung, is laying plans to begin experimental studies of unsteady separation in the near future. This would complement their existing research on separation from bluff and streamline bodies at high angles of attack. To improve their visibility in unsteady flow fields, Hornung's Institute is hosting the AGARD Conference in May 1985 on Unsteady Aerodynamics - Fundamentals and Applications to Aircraft Dynamics.

College of Aeronautics
Cranfield Institute of Technology
Cranfield, Bedford, U.K.

This institute has only a post-graduate curriculum and is orientated toward the more practical side of the aircraft industry. Many courses on airworthiness, causes and investigations of aircraft accidents, performance and aircraft economy are offered to their M.S. students. In a similar manner, the research of the faculty and Ph.D. students tends to be applied investigations, often involving modifications to aircraft operated by the institute. For example, one present project is to study the aerodynamics of flexible wing structures using a full scale hang glider mounted above a moving vehicle. Some joint work with the Royal Aircraft Establishment at Bedford a few miles away is also undertaken. Aerodynamics of trucks, mobile homes and other bluff bodies has been studied here also. There is presently no research on unsteady aerodynamics.

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