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SECURITY CLASSIFICATION OF THIS PAGE

DTIC ELECTE OCT 1 3 1988 D H

AD-A199 989

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS
NONE

3. DISTRIBUTION/AVAILABILITY OF REPORT
APPROVED FOR PUBLICATION AND RELEASE;
DISTRIBUTION UNLIMITED

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 88-1138

6a. NAME OF PERFORMING ORGANIZATION
UNIVERSITY OF SOUTHERN
CALIFORNIA

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
AFOSR

6c. ADDRESS (City, State and ZIP Code)
UNIVERSITY PARK
LOS ANGELES, CA 90089-1147

7b. ADDRESS (City, State and ZIP Code)
DIRECTORATE OF SPACE SCIENCES
BLDG. 410, BOLLING AIR FORCE BASE
WASHINGTON, D.C. 20332-6448

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
AFOSR /NA

8b. OFFICE SYMBOL (If applicable)
NA

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F49620-85-C-0080

8c. ADDRESS (City, State and ZIP Code)
Building 410
Bolling AFB, DC 20332-6448

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2307	A2	

11. TITLE (Include Security Classification)
Studies of Unsteadiness in Boundary Layers

12. PERSONAL AUTHOR(S) CO-PRINCIPAL INVESTIGATORS: RON F. BLACKWELDER, CHIH-MING HO, PATRICK HUERRE AND LARRY REDEKOPP

13a. TYPE OF REPORT
ANNUAL TECHNICAL

13b. TIME COVERED
FROM 5/01/87 TO 4/30/88

14. DATE OF REPORT (Yr., Mo., Day)
7/13/88

15. PAGE COUNT
16

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Turbulence, Boundary Layer, Jets, Chaos

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

EXPERIMENTAL AND THEORETICAL EFFORTS AIMED AT CLARIFYING AND REVEALING IMPORTANT DYNAMICAL FEATURES OF SEVERAL TURBULENT SHEAR FLOWS ARE DESCRIBED. THE FLOWS, STUDIED INCLUDE BOUNDARY LAYERS, JETS, WAKES AND SEPARATED FLOWS ON LIFTING SURFACES. SIGNIFICANT PROGRESS HAS BEEN MADE THROUGH EXPERIMENTAL STUDIES TOWARD UNDERSTANDING:

1) UNSTEADY, NEAR-WALL PROCESSES IN TURBULENT BOUNDARY LAYERS RESPONSIBLE FOR THE PRODUCTION OF TURBULENT ENERGY;
2 ~~ii~~) PROCEDURES FOR ENHANCING ENTRAINMENT AND MIXING IN HOT JETS BY PASSIVELY CONTOURING THE JET EXIT; AND
3 ~~iii~~) CHARACTERISTICS OF BOUNDARY LAYER SEPARATION AND ITS CONTROL ON LIFTING SURFACES IN UNSTEADY FLOWS.

THEORETICAL STUDIES ON THE TEMPORAL AND SPATIAL STRUCTURE IN BLUNT-BODY WAKES HAVE REVEALED THE NECESSARY CONDITIONS UNDER WHICH GLOBAL, SELF-SUSTAINED OSCILLATIONS APPEAR AND HAVE PROVIDED FIRM CRITERIA FOR SPECIFYING THE FREQUENCY OF THESE OSCILLATIONS. THE

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

→ next page

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DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

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SECURITY CLASSIFICATION OF THIS PAGE

88 1011 18[illegible]

THEORY HAS ALSO BEEN EMPLOYED TO DESCRIBED THE PREFERRED MODE IN JETS. IN ADDITION, A THEORETICAL DESCRIPTION OF THE APPEARANCE OF THE SPATIAL CHAOS IN WAKE SHEAR LAYERS, AND ITS REPRESENTATION IN TERMS OF A ONE-DIMENSIONAL MAP, HAS BEEN PROVIDED.

AFOSR-TR- 88-1138

Accession For	
NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

ANNUAL SCIENTIFIC REPORT

(May 1, 1987 - April 30, 1988)

for

AFOSR-TR- 88-1138

AFOSR Contract F49620-85-C-0080
Department of Aerospace Engineering
University of Southern California
University Park
Los Angeles, CA 90089-1191

Task 1: Studies of Unsteadiness in Boundary Layers

by

Ron Blackwelder, Principal Investigator

Objectives

Examine the effects of Reynolds number on the near wall eddy structure in order to more distinctly separate the differences observed as the Reynolds number increases.

Explore an equilibrium turbulent boundary layer undergoing an adverse pressure gradient and examine in detail the wall layer eddies to understand how they are affected by pressure gradients.

Study the physical mechanisms by which turbulence is produced by the interaction of the low speed streaks and the ejections in boundary layers.

Re-install the Gortler wind tunnel in the newly completed Rapp Research Building and begin a study of unsteady effects on the emulated wall structure.

Investigate the wall layer structure by visualizing multiple particles with automated tracking to obtain all velocity components in a three-dimensional region at one instant in time.

Results

The effect of Reynolds number dependence in the wall region has been an open question for many years. On the one hand, modelling methods suggest that the wall layer of a turbulent boundary layer should be independent of the outer region and hence independent of the Reynolds number. On the other hand, some experimental evidence and mathematical expansion techniques indicate that there is an influence, albeit weak, of the Reynolds number on the wall region. This influence was examined by measuring the spanwise correlations, R_{uu} ($\hat{}z$), at $y^+ = 15$ over a Reynolds number range of $10^3 < Re_\theta < 10^4$. At $Re_\theta > 2000$, the characteristic negative region of the correlation disappeared as seen in Figure 1. In addition, the integral scale of the spanwise correlations increased linearly with Re_θ. Considerable effort was taken to insure that these results were not due to spatial averaging imposed by the sensors which typically have a larger non-dimensional length as the Reynolds number increases. For example, figure 1 shows data at Reynolds numbers of 4200 and 7600 which have the same non-dimensional sensor length. The correlations are considerably different indicating a Reynolds number effect in this aspect of the eddy structure. This result does not necessarily contradict the previous work of Smith and Metzler (J. Fluid Mech., 129, 27, 1983) which found that the spanwise spacing of the low speed streaks was constant for $740 < Re\theta < 5830$. However it does imply that as the Reynolds number increases, the flow field becomes more random and/or additional eddy structures make their presence felt in the wall region.

A mildly adverse pressure gradient has been established in the wind tunnel which has a Beta parameter of 0.9 corresponding to similar pressure gradients studied by Clauser and Bradshaw. The purpose of the present study is to make detailed measurements of the near-wall structure which has been ignored in the past. This necessitated that the Reynolds number be lower in the present case so that the length scales in the wall region are not small compared to the scale of the sensors. Space-time correlations $R_{uu}(\hat{}z, \hat{}x)$ (where $\hat{}x$ is obtained using Taylor's hypothesis) were measured in the zero and adverse pressure gradient. As the boundary layer undergoes the adverse pressure gradient, the isocorrelations of $R_{uu} > 0.2$ at $y^+ = 15$ show very little change indicating that the small scale structure survives the pressure gradient intact and is independent of the pressure gradient. However the lower level correlations become broader in the streamwise and spanwise directions indicative of the increased presence of the large scale outer structure.

The detailed turbulence production mechanism has been studied using an experimental model of the eddy structures near the wall. The model consists of weak counter-rotating streamwise vortices lying in a strong $\partial U/\partial y$ shear. To avoid the uncontrollable randomness in a turbulent flow, a laminar boundary layer was used to provide the strong shear near the wall. As light amount of curvature was used to generate counter-rotating streamwise vortices via a Gortler instability mechanism. The experimental configuration was chosen so that the vortices were weak; namely the secondary vorticity had $\omega_x << \omega_z$. The presence of the weak streamwise vortices in the strong $\partial U/\partial y$ shear provides an important momentum transport mechanism; namely only a small amount of rotation is required to drastically alter the distribution of the mean momentum. Consequently low speed momentum accumulates between alternating vortices to form elongated regions of low speed fluid akin to the low speed streaks in the turbulent case. The principal results from this effort has been to show that the low speed streaks develop strongly inflectional profiles around their upper surface in the emulated flow. Correspondingly in the turbulent case, instantaneous data obtained from rakes of hot-wires in the spanwise and normal directions show that there are numerous inflection points in directions parallel and perpendicular to the wall as seen in figure 2. Michalke's (1965, J.Fluid Mech., 23, 521) analysis of the stability of similar profiles indicates that they are highly unstable and develop an oscillation with a wavelength of $\lambda_x = 15.7$^ where ^ is the thickness of the shear layer. This agrees with the observed experimental results in both the emulated flow and the turbulent flow. In addition, Michalke found that the oscillations have very rapid growth rates; i.e. their amplitude increases by a factor of 35 while travelling one wavelength downstream. This conforms to the observed breakdown of the oscillations after travelling only one or two wavelengths downstream. Even though Michalke's analysis is for a two-dimensional unbounded steady profile, evidence in the literature suggests that departures from these conditions do not substantially alter the mechanism of the instability. The primary conclusion is that normal and spanwise shear layers can produce large u, v, and w fluctuations in the wall region which can not be accounted for by the Reynolds averaged concept. Present efforts are directed towards adding a large vortical eddy structure which will emulate the large scale eddies in the outer flow field of a turbulent boundary layer as discussed in the following paragraph.

During the past year the Rapp Research Building was completed and the Gortler wind tunnel was removed from storage and reassembled in the new laboratory. A mechanism to emulate the large scale eddies of the outer region of a turbulent boundary layer has been designed and is being built. It consists of an oscillating airfoil suitably scaled to yield the appropriate time and spatial structure of the large eddies. The airfoil will be driven by a stepping motor so that different vorticity distributions, and hence eddy structures, can be obtained by changing the waveform of the driver. In the meantime, a short study of the interaction of a Tollmien-Schlichting waves and the Gortler instability has been undertaken. This problem is important on concave regions of modern airfoils in the transitional regime. It has been studied by Nayfeh (J. Fluid Mech., 107, 441, 1983) analytically but has not been examined experimentally. Similar techniques for data processing and reduction are common to both this problem and the emulated unsteady boundary layer, and hence most of the programs for data analysis for both projects are being developed. This project will be completed by mid-summer 1988 and the emulated boundary layer with the unsteady outer structure continued.

An additional project was undertaken this year prompted by the visit of Dr. T. Utami from the Ujigawa Hydraulics Laboratory in Kyoto, Japan. An experimental technique was developed that allowed the three-dimensional velocity field to be obtained from a volume in space at a fixed time instant. The method utilized photographs taken in rapid succession of particles in a channel flow that were illuminated by a sheet of light. The light sheet was thin so that it illuminated only particles in a well defined x-z plane. Two photographs taken at a ^t time difference were digitized and analyzed via image processing programs. By tracking the particle pairs, the u and w velocity components could be obtained in the plane. Other photographs were also taken sequentially in nearby x-z planes a short time later by rapidly moving the light sheet. Analyzing these photos yielded the u and w velocity components in all planes. Since the photographs were all taken with only a small time difference between them, the normal velocity component v could be obtained by integrating the continuity equation. The results were checked by comparing mean and higher order statistics with previous data. In addition, the spatial correlations, R_{ij} (^x, ^z), were computed for i and j=1, 2 &3 and compared with similar correlations obtained especially for this project from the numerical data base at NASA Ames by Steve Robinson and at the Naval Research Laboratory by Robert Handler. All of these results agreed quite well indicating that the technique is indeed viable and offers a new and exciting method for obtaining three-dimensional velocity data.

Invited Talks and Honors

Keynote Address at the 2nd International Symposium on Transport Phenomena in Turbulent Flows, at the University of Tokyo, October 25-29, 1987.

Publications

1. "A Hot-Wire Probe for Velocity Measurement in Reversing Flows", R. F. Blackwelder and Ian McLean, Symposium on Thermal Anemometry, Ed. D. E. Stock, Am. Soc. Mech. Eng., FED-Vol 53, 1987.

2. "Coherent Structures Associated with Turbulent Transport", Ron F. Blackwelder, to appear in Turbulent Transport, Ed. M. Hirata and N. Kasagi, Hemisphere Pub. Co.

3. "The Growth and Breakdown of Streamwise Vortices in the Presence of a Wall", J.D. Swearingen and Ron F. Blackwelder, J. Fluid Mech. 182, 255, 1987.

4. "The Role of Inflectional Velocity Profiles in Wall Bounded Flows", Ron F. Blackwelder and Jerry D. Swearingen, 1988, Int'l Seminar on Near Wall Turbulence, Hemisphere Pub. Co.

5. "Flow Visualization with Image Processing of Three-Dimensional Features of Coherent Structures in an Open Channel Flow", T. Utami, R. F. Blackwelder and T. Ueno, Int'l Seminar on Near Wall Turbulence, Hemisphere Pub. Co.

6. "Modification of Turbulent Boundary Layers Using Large Eddy Breakup Devices", S. -I. Chang and Ron F. Blackwelder, to be submitted to the J. Fluid Mech.

Professional Personnel

Ron F. Blackwelder: Principal Investigator

Tadashi Utami: Visiting Scholar

Shi-Ing Chang: Graduate and Post-doctoral student

Ian Mclean: Graduate student

Roy Myose: Graduate student

Shi-Ing Chang: Awarded a Ph.D. degree in June 1987 for a thesis entitled "Modification of Large Eddies in a Turbulent Boundary Layer.

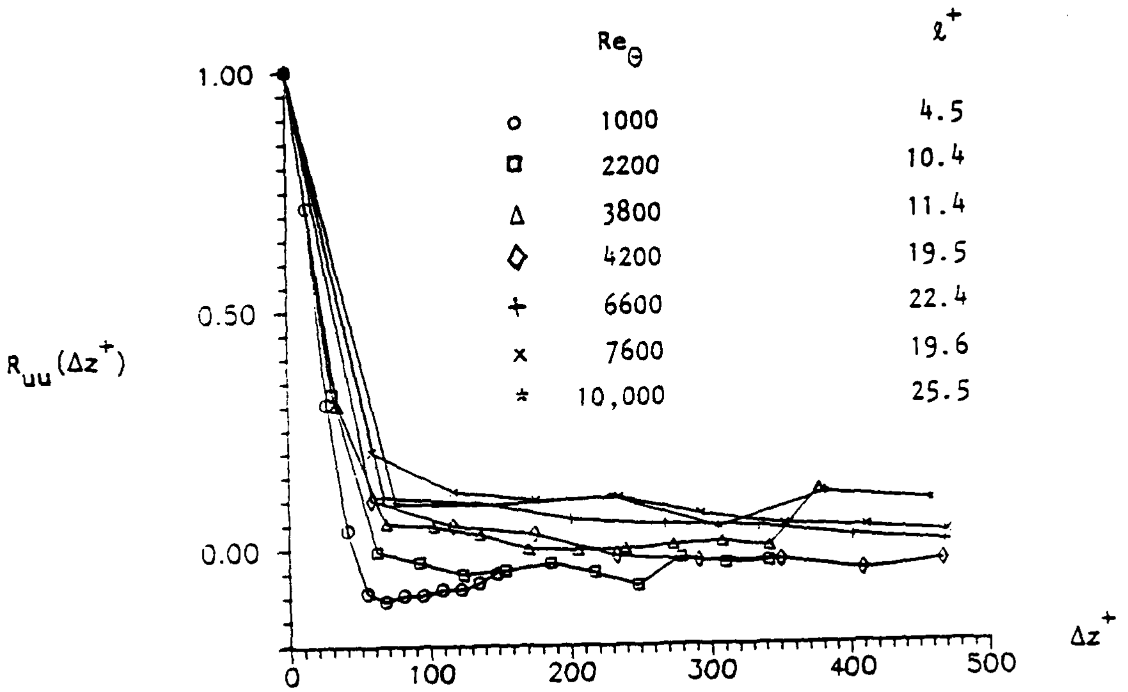

Figure 1. R_{uu} (Δz^+) at y^+=15 for seven different Reynolds numbers.

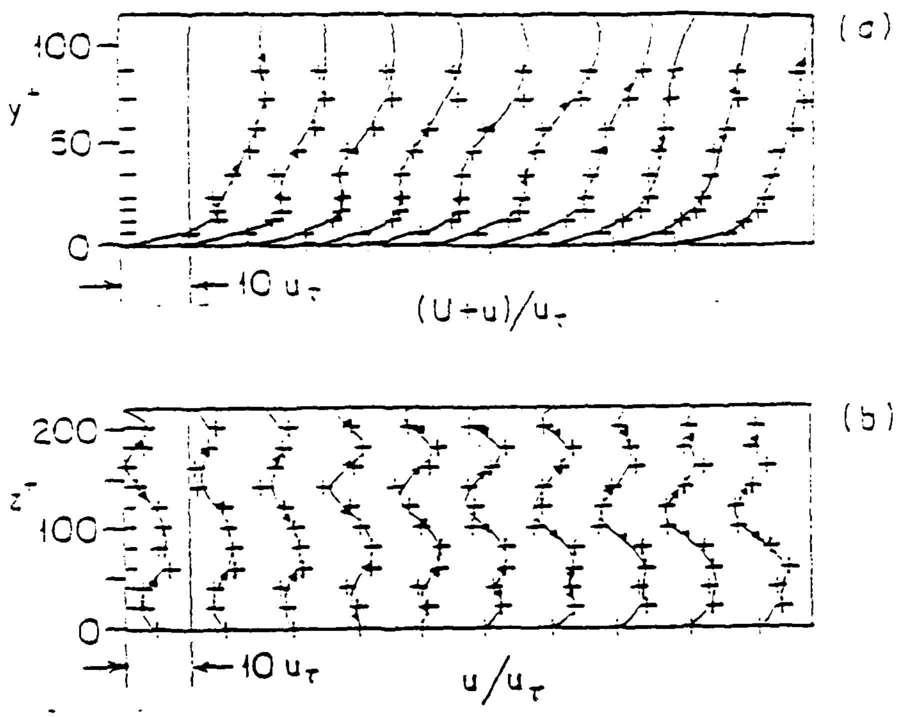

Figure 2. Instantaneous turbulent boundary layer profiles from hot-wire sensors of the streamwise velocity component in the (a) normal and (b) span-wise directions. The data points are indicated by (+) and a spline fit yielded the lines. The points of inflection (◄) were obtained from the spline function. The time between profiles is $1.5\nu/u_\tau^2$ in (a) and $1.0\nu/u_\tau^2$ in (b).

TASK 2: UNSTEADY SEPARATION AND UNSTEADY SHEAR LAYERS

by

Ho, Chih-Ming: Principal Investigator

SUMMARY

In the unsteady aerodynamics study, the responses of a 2-D and a delta wing under a time-varying free stream was investigated in a uniquely designed water channel. We study this problem from the point of view of vorticity generation and convection. Based upon this approach, a fundamental understanding of the unsteady aerodynamics is obtained.

In the control of shear layer study, the hot eliptic jet can entrain 25% more fluid than the cold one. This evidence shows that the temperature gradient can modify the vorticity distribution of the elliptic vortex, such that the vortex deformation caused by the self-induction is more efficient in engulfing the fluid.

Unsteady Aerodynamics

Vorticity Concepts

From experimental evidences, it was found that vortex dynamics is important in unsteady separated flows. Concepts based upon the fundamental fluid dynamics aspects were proposed with an emphasis on the vorticity balance.

The vorticity generation from the airfoil surface is determined by the local pressure gradient,

$$[\nu\ (d\omega/dy)]_s = [(-1/\rho)\ (dP/dx)]_s, \qquad (1)$$

while the transport of the vorticity is governed by the well-known vorticity transport equation,

$$D\omega/Dt = \nu \nabla^2 \omega. \tag{2}$$

According to this relationship, the vorticity distribution of the airfoil, which is determined by the balance of the vorticity convection and production, can be reorganized by unsteadily modulating the free-stream velocity. The aerodynamic properties, which depend on the distributed vorticity pattern, can therefore be understood through basic vorticity concepts.

Three-Dimensional Structures of 2-D Wing

Two-dimensionality of the oncoming free-stream flow was first established when the flow separated from the airfoil. Distinct three-dimensional structures were observed from the spanwise distributed velocity profiles. Away from the center of the span, upward distortions of the separated vortex line were found to be responsible for the initial 3-D excursion. At a later phase, this spanwise non-uniformity induced secondary vortices off the centerline of the airfoil, and further exacerbated the situation. During the acceleration, the flow gradually became attached and recovered its two-dimensionality.

Lift and Circulation Correlation of 2-D Wing

The response of the airfoil to the unsteady flow is indicated by the phase-averaged lift coefficient, C_L, and the total circulation profiles as shown in Figures 1 and 2. During the deceleration, a vortex emerged due to an imbalance of the vorticity convection, see also the increase of the circulation during this phase. The subsequent evolution of this vortex therefore controlled the C_L patterns, which is a convection-dominated process. The gradual migration of the curves was identified as a result of a mismatch between vortex roll-up and convection time scales and the deceleration time period. During the acceleration, the flow attached from the leading edge to the trailing edge. Universal behaviors developed for both the C_L curves and the circulation data, as they all collapsed into a single curve, see Figures 1 & 2.

Delta Wing

When the delta wing was subjected to the unsteady free-stream, the leading edge vortices were not very much affected by the imposed unsteadiness. The most interesting finding as a consequence of the robustness of the vortices is that the difference between the phase-averaged C_L and the static C_L follows the time derivative of the free-stream velocity with minimal phase lag. This finding suggests that the unsteady lift is generated by the inertia of the oncoming flow.

Entrainment Control

In the previous elliptic jet experiment, we found that an elliptic jet with a small aspect ratio could entrain several times more fluid than a 2-D jet. The main advantage is that it is a passive control technique, no fancy forcing device is necessary. The most important finding, perhaps, is that we identify a new, other than the vortex merging, entrainment mechanism. The self-induction of the asymmetric vortex ring makes the structure deform in the azimuthal direction, such that the elliptic vortex switches its orientation. During the axis-switching the minor axis moves outward and a large amount of the ambient fluid is entrained into the jet. This mechanism is much more effective than the vortex merging.

In fast chemical reactions, this process is limited by the mixing. Therefore, entrainment control can improve the efficiency of the combustion devices. In the present experiment, we use a hot jet to investigate the effect of temperature on the vorticity distribution of the elliptic vortex, such that the heat effect can be isolated from other influences.

The original elliptic jet was modified to run at a much higher speed, 250 ft/sed, and at 500°F. The velocity profiles at each downstream location were surveyed in a quadrant of the ellipse. The mass flow rate was integrated from the velocity data and compared with the homogenous jet [Figure 3]. The entrainment rate of a hot jet is about 25% higher than that of a homogeneous jet. This interesting result implies that the self-induction process can be changed with the use of heat. It is possible that the temperature gradient between the cold ambient air and the hot jet modifies the vorticity distribution. The deformation of the structure caused by the self-induction around the elliptic vortex must then be modified. The time averaged axis-switching location is shown in Figure 4. These curves do show that the axis-switching position of the hot jet moves upstream.

FUTURE WORK

Unsteady Aerodynamics

The new unsteady water channel has been completed. Future experiments will be performed in this channel. We found that the vorticity production and the convection play major roles in the lift variations. At present, the convection portion can be measured accurately but the production term is not well determined by the LDV. The best way to do it is to measure the surface pressure gradient that offers the vorticity diffusion from the surface. This approach will be our future efforts.

Entrainment Control

The significant difference in the entraiment and the axis-switching position for a hot and a homogenous jet can help us in further understanding the new entrainment mechanism - azimuthal deformation by self-induction. More specifically, the heat can be used as a tracer to tag the jet fluid and distinguish it from the ambient fluid. We are building and calibrating a two-wire probe, one is a cold hot-wire and another is a hot-wire. The instantaneous velocity and temperature signals can be resolved from the probe outputs. It is then possible to link the entrained fluid to the vortex deformation. Based upon these information, better control method can be developed.

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4. "Leading Edge Separation over a Delta Wing", Lee, M., Shih, C., and Ho, C.M., Proc. of ASME Fluids Engineering Spring Conference, 1987.
5. "Wave Structures in Jets of Arbitrary Shape. III. Instability Analysis of Elliptic-Core Jets", Koshigo, S., Tubis, A., and Ho, C.M., to appear in Phys. of Fluids, 1988.
6. "Unsteady Separation over Two- and Three-Dimensional Airfoils", Shih, C., Lee, M., and Ho, C.M., Proc. Workshop on Unsteady Separated Flow, 1987.
7. "Application of a Generalized Shooting Method to the Linear Instability Analysis of Elliptic Core Jets", Koshigo, S., Ho, C.M., and Tubis, A., AIAA Paper

87-2733, 1987.

8. "Vortex Dynamics of a Delta Wing: A Review", Lee, M. and Ho, C.M., to appear in Lecture Notes of Engineering, Pub. by Springer.

PROFESSIONAL PERSONNEL

Professor Ho, Chih-Ming: Principal Investigator

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Task 3: Search for Chaos in Free Shear Flows: the Case of the Wake Shear Layer

by

Patrick Huerre and Larry Redekopp
Co-Principal Investigators

SUMMARY

Simple theoretical models have been developed to describe the onset of global modes in wakes behind bluff bodies, the appearance of spatial chaos in wake-shear layers and the existence of a preferred mode in jets. The results are in good qualitative agreement with laboratory observations.

OBJECTIVE

The main objectives of this study are concerned with the characterization of global modes in mixed flows (absolutely unstable in one region and convectively unstable in another region) and with the identification of deterministic chaos in wake shear layers. The project is conducted as a coordinated analytical-numerical-experimental effort involving model systems, numerical simulations and laboratory experiments.

STATUS OF RESEARCH EFFORT

Significant progress has been made in the following areas:

* Theoretical models based in the Ginzburg-Landau equation [2, 6] have shed considerable light on the relationship between the existence of global modes and local instability properties in spatially-developing flows. It has been shown that the sequence of bifurcations to local and global modes exhibited by the model is entirely consistent with observations of wakes behind bluff bodies [7,8]. In particular there must be a region of absolute instability of finite extent for the flow to support self-sustained resonances. The study of simple amplitude evolution models has also indicated that primary and secondary instabilities may have a distinct absolute/convective character

within the same physical flow [1]. This feature should have important implications for transition in boundary layers where secondary instabilities are known to play a crucial role. Finally, we have used the Ginzburg-Landau model to obtain a simple description of the preferred mode in jets [3, 4]. Its predominance is the result of selective temporal amplification due to the small negative absolute growth rate prevailing at approximately one diameter downstream. This model allows a surprisingly good prediction of the preferred mode characteristics.

- The interaction between sinuous and varicose modes in wake-shear layers has been described in terms of coupled amplitude evolution equations in the viscous critical layer regime [5]. In this range, the nonlinear system can be derived asymptotically from the Navier-Stokes equations. A detailed numerical study of the resulting dynamical systems has revealed a great variety of possible spatial vorticity distributions as the forcing frequency is gradually increased. In particular one may obtain a chaotic distribution of vortices with the intermittent appearance of the varicose mode along the stream. This intermittency has been used to advantage to derive an analytical representation of the one-dimensional map underlying the dynamics of the flow field. Thus, by a series of rational approximations, one has reduced an infinite-dimensional (in phase space) hydrodynamical system to a one-dimensional map which captures all the essential features of the flow.

- The water channel designed to conduct wake experiments has been tested. Turbulence management sections have been finished. The hot film instrumentation has been tested and we are in the process of assembling the control device of the traverse mechanism. Measurements will then be undertaken to survey the flow quality of this water channel.

PUBLICATIONS

1. Huerre, P. "On the Absolute/Convective Nature of Primary and Secondary Instabilities", to appear in Springer Proceedings in Physics, (Proceedings of Workshop on "Propagation in Far From Equilibrium Structures", Les Houches, France, March 10-18, 1987).

2. Chomaz, J.M., Huerre, P. and Redekopp, L.G., "Models of Hydrodynamic Resonances in Separated Shear Flows", to appear in the Proceedings of the Sixth Symposium on Turbulent Shear Flows, Toulouse, France, September 7-9, 1987, Springer Verlag.

3. Monkewitz, P.A., Huerre, P. and Chomaz, J.M., "Preferred Modes in Jets and Global Instabilities", Bulletin of the American Physical Society, Vol 32, p. 2051, 1987.

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5. Sauliere, J. and Huerre, P., "Spatial Chaos and Nonlinear Interactions in Wake-Shear Layers", Bulletin of the American Physical Society, Vol. 32, p. 2071, 1987.

6. Chomaz, J.M., Huerre, P. and Redekopp, L.G., "Bifurcations to Local and Global Modes in Spatially-Developing Flows", Physical Review Letters, Vol. 60, pp. 25-28, 1988.

7. Monkewitz, P.A. and Nguyen, L.N., "Absolute Instability in the Near-Wake of Two-Dimensional Bluff Bodies", Journal of Fluids and Structures, Vol. 1, pp. 165-184, 1987.

8. Monkewitz, P.A., "The Absolute and Convective Nature of Instability in Two-Dimensional Wakes at Low Reynolds Numbers", to appear in Physics of Fluids.

INVITED TALKS

1. "Dynamique des Structures Coherentes et Ondes d'Instabilite dans la Ecoulements Cisailles", P. Huerre, Special Seminar, Universite d'Orsay, Paris, France, September 11, 1987.

2. "Spatio-Temporal Dynamics in Free Shear Flows", Invited Lecture, P. Huerre, 40th Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Eugene, Oregon, November 24, 1987.

3. "Large-Scale Dynamics in Free Shear Flows", P. Huerre, Nonlinear Science Seminar, University of California, Santa Barbara, January 22, 1988.

4. "Local and Global Evolution of Instability Waves in Free Shear Flows, P. Huerre, Fluid Mechanics Seminar, California Institute of Technology, Pasadena, January 29, 1988.

5. "Local and Global Evolution of Instabilities in Free Shear Flows", P. Huerre, Seminar in Fluid Dynamics, University of California, San Diego, February 23, 1988.

6. "Global Instability and Chaos in Free Shear Flows", P. Huerre, Department of Mechanical and Materials Engineering Seminar, Washington State University, Pullman, March 9, 1988.

7. "Spatial Chaos and Sensitivity to Forcing in Wake Shear Layers", J. Sauliere, Special Seminar, Department of Aerospace Engineering, University of Southern

California, April 8, 1988.

PROFESSIONAL PERSONNEL

Dr. P. Huerre: Co-Principal Investigator.

Dr. L.G. Redekopp: Co-Principal Investigator.

Dr. J.M. Chomaz: Research Associate.

Mr. J. Sauliere: Research Assistant.

Mr. G. Vance: Research Assistant.