DYNAMICS AND CONTROL
of
TURBULENT SHEAR FLOWS

Report of Research Activities

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A Research Program

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DEPARTMENT OF AEROSPACE ENGINEERING

UNIVERSITY OF SOUTHERN CALIFORNIA

Los Angeles, California 90089-1191

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DYNAMICS AND CONTROL OF TURBULENT SHEAR FLOWS

EXECUTIVE SUMMARY

1 SCIENTIFIC OBJECTIVES

The objectives of this research program are summarized in three statements.

a) Provide a DYNAMICAL DESCRIPTION of various turbulent shear flows having technological significance.

b) Define the CONTROLLABILITY of key dynamical events and processes which impact global, engineering performance measures.

c) Formulate effective and efficient CONTROL STRATEGIES for specific types of flows and performance measures.

Research progress toward these goals is summarized in eight separate reports following the Executive Summary. These reports set forth the goals accomplishments, and future plans of different sub-projects led by individual, or teams of, co-investigators. There is a considerable amount of interaction and cooperative effort among different co-investigators on several topics (free shear layer dynamics and Görtler instability, in particular), but no attempt has been made to merge combined efforts on an individual topic into a single report.

2 RESEARCH PERSONNEL

The team of co-investigators consists of seven full-time faculty and one adjunct professor from the Aerospace Engineering department and one faculty member with a joint appointment in both the Aerospace Engineering and the Mechanical Engineering departments. As presently comprised, this research team represents several changes in personnel since the beginning of the project. First, a change in directorship of the project was made during the first fiscal year. Professor R. E. Kaplan, the project director and chairman of the Department of Aerospace Engineering, left the project in March 1987 to assume the position of Vice-Provost for Computing within the university administration. The department administration has been reorganized under two co-chairmen, Professors E. P. Muntz and L. G. Redekopp. Professor Redekopp, an original co-investigator on the the project, is now serving as project director with Professor R. F. Blackwelder serving as assistant director. A second change involved the addition of Professor J. A. Domaradzki as a co-investigator. Professor Domaradzki joined the department as an assistant professor in January 1987. His expertise is in the area of computational fluid dynamics with considerable experience in the computation of turbulent flows. Professor Domaradzki was, for the first two and one-half years, supported by institutional funds as promised from the USC School of Engineering through a Powell Foundation Grant in support of the ONR-URI program. In October 1989 he will begin receiving partial support from ONR-URI funds. A third change was instituted in October 1988 when Dr. R. H. Liebeck, an adjunct professor in Aerospace Engineering was added to the research team. Professor Liebeck is renowned for his expertise in wing theory and design practice and is, together with Professor Blackwelder, supervising a project on the control of laminar separation bubbles on low Reynolds number airfoils. A report of the activity on this topic is included in the Research Reports section.

Project funds have provided training support for a substantial group of research personnel. This includes half-time support for a post-doctoral research fellow (Dr. J. Hertzberg), support for six Ph.D. students (H. Asano, E. Ikeda, P. LeBlanc, D. Park, J. Roon and J. Wiggert), support for two M.S. students who have already completed their studies (F. Pray and S. Prost-Domasky), plus support for several undergraduate laboratory assistants. Institutional funds derived from the Powell Foundation have provided support for an additional Ph.D. student (Liu Wei).

3 BUDGETARY ISSUES

Funding uncertainties and variations over the last two years have had a measureable impact on the overall program and its management. During the second fiscal year (October 1, 1987 to September 30, 1988), the budget was reduced by 39.4% from that originally proposed. During the current fiscal year (i.e., the third year of the project) the budget has been reduced 23.1% compared to the originally proposal amount. These reductions forced several revisions of the research plan, impacted graduate student recruitment, prevented appointment of two post-doctoral researchers, slowed the development of several experimental facilities, postponed some equipment purchases, and caused us to significantly reduce the participation of the co-investigators during the summer months. Some of the impact of these cuts was softened by judicious use of Powell Foundation funds ($ 70K/yr.). However, those funds were only committed for project use during the first-three years of the program and, hence, careful planning is required so as to sustain the vitality of the program in the face of reduced discretionary resources.

4 INSTRUMENTATION AND FACILITIES

In spite of the budgetary variations, the ONR-URI project has had a major impact on laboratory instrumentation and facilities. Two major facilities have come on line since the beginning of the project: a large water channel and an isothermal dump combustor facility. The large water channel is currently being prepared and instrumented for studies in turbulent boundary layer control with application to drag reduction. The dump combustor facility has already been used extensively for studies of passive control of mixing enhancement in confined geometries. A third facility is currently being tested for use in studies of the Görtler instability. The latter facility was delayed considerably as a consequence of the aforementioned budget adjustments.

ONR-URI funds were used to significantly enhance the instrumentation capability in our laboratory. Most importantly, we purchased two Laser-Doppler Velocimeter systems which are being used in conjunction with experiments in the large water channel and the dump combustor facility. Due to budget limitations, the LDV systems that were purchased were downgraded from the two, 2-component systems which were part of our original equipment proposal. Instead, we purchased limited optics and only one signal processing unit so the two systems are presently only capable of measuring one velocity component. Enhancements required to make both systems operate as independent, 2-component LDV systems will depend on future budgets. In addition to these major instrument purchases, project funds have been used to purchase six hot-film channels, fourteen hot-wire channels, together with a variety of other laboratory instruments like oscilloscopes, transducers, amplifiers, etc.

Another area where this project has had a major impact is in the area of computational and data analysis capabilities. Together with institutional support through the Powell Foundation, ONR-URI funds have been used to dramatically increase our computational environment through hardware purchases (six SUN 3/50 workstations, one SUN 3/60 color workstation, one SUN 3/280 fileserver, four Maxum 286 Turbo PCs, two 60 mb tape drives, one Apple Laser Printer, one HP Laser-jet Printer, one HP Graphics plotter, and five 16-channel A/D converters) plus several major software purchases and a high-speed link to the San Diego Supercomputer Center.

5 LABORATORY INTERACTION

We have had extensive and profitable interaction with several scientists from the Naval Weapons Center at China Lake, CA over the duration of the project. A goodly number of exchange visits between NWC personnel (Drs. Schadow, Koshigoe and Gutmark) and USC co-investigators (Professors Ho and Huerre) have occurred thus far and we anticipate a continuation of this interaction. The subject of this interaction is jet mixing for supersonic combustion and scram-jet technology.

Quite recently we have begun an interaction with the Naval Underwater System Center at Newport, RI regarding the effect of particulates on boundary layer transition. This interaction involves Dr. Duncan Brown and his associates at NUSC and Professors Blackwelder and Browand at USC. The present plans include some experiments in the large water channel at USC which was brought on line and instrumented by URI funds.

Another area of interaction is with the LAURA (low altitude unmanned research aircraft) project at NRL and the HALE (high altitude long endurance) project at NADC. Professors Liebeck and Blackwelder are guiding research efforts along these lines and Professor Liebeck has been involved with the evaluation team at NRL for the LAURA project.

Professor Huerre visited NRL and, in addition to presenting a seminar, had discussions with several researchers concerning the dynamics of mixing layer flows. He also participated in and gave an invited lecture at the "Joint ONR/AFOSR Colloquium on Active Control and Turbomachinery Hydroacoustics" in May 1988.

We have also had extensive interaction with the turbulence research group at the NASA Ames Research Center. Professor Blackwelder was a visiting scientist at the Center for Turbulence Research summer program in 1987, and Professors Domaradzki, Ho, and Huerre participated as visiting scientists in the 1988 summer program. Professors Ho and Huerre each presented tutorial lectures on topics related to turbulent mixing. Joint research efforts with scientists at NASA Ames and USC co-investigators are on-going.

BOUNDED SHEAR FLOWS – EXPERIMENTAL APPROACHES

Principal Investigator: R. F. Blackwelder

Research Summary

Description of Scientific Research Goals

The principal objective of the research is to understand the dynamics of the bursting process well enough that a significant reduction in drag can be achieved. If the low speed streaks associated with the bursting phenomenon in a turbulent boundary layer can be prevented from lifting away from the surface, then the bursting process would be disrupted. Hence turbulent production would be reduced, and a lower drag should follow. The first problem is that the low speed streaks occur randomly in space and time. Research into aligning these low speed streaks using wall roughness elements has been performed. Selective suction has been used to prevent the streaks from lifting off the wall. By using our knowledge of the eddy structure and selectively interacting with it, significantly less suction should be needed than for standard boundary layer control.

Significant Results

Cylindrical rods of $4\nu/u_\tau$ in diameter aligned in the streamwise direction were placed on the wall of the flat plate model. These longitudinal roughness elements (denoted by LREs) acted as nucleation sites for the formation of the low speed regions. For $y^+ < 10$, these LREs reduced the meandering of the low speed streaks such that the streaks were always close to one of the elements. Thus the probability of finding a streak at a particular location was greatly improved. This control method is quite important if one wants to modify the low speed streaks which usually appear randomly in space and time.

The LREs were used to anchor the streaks into known locations and then suction was applied. The suction was generated over a 3.5cm × 3.5cm area with the fluid withdrawn through a porous plate under the roughness elements. The amount of suction was controlled by a variable speed pump and was applied selectively under the streaks by masking portions of the porous plate between the LREs. Figure 1 shows that, above each of the LREs, the mean velocity was reduced by 1.5 - $2.0u_\tau$ at $y^+ = 12$ depending upon the amount of suction. This results from the elevated no slip condition on the LREs and supports the results that the low speed streaks were less random. The number of streaks, N, were counted using an algorithm that determined the number of times the velocity crossed below a fixed threshold. The threshold was one rms value below the mean velocity measured on the clean flat plate. As expected, the number of streaks decreased considerably as the suction was applied (cf., Figure 2). Even when the threshold was adjusted for the new local mean and rms values, the detected number of low speed streaks was reduced as the suction increased.

The suction increases the net drag as manifested by the increased mean velocity at a fixed elevation above the wall (cf., Figure 1). However, the intent of the suction was to prevent the low speed streaks from lifting and forming the ejection phase of the motion which should reduce the turbulence production downstream. A measure of this activity is shown in Figure 3 in which the shear layer detection frequency obtained by the VITA technique was measured. The detection parameters were not altered from those used on the clean flat plate. The detection frequency decreased slightly when the LREs were added and decreased further with the suction. The total decrease shown in Figure 3 is 20-30%, suggesting that this method may offer some means of control of the near wall eddies.

To provide for a zero mass flow system, the fluid removed from beneath the low speed streaks must be added back into the wall region, possibly beneath the higher speed regions (although this has not been attempted). This selective injection would reduce the gradient at the wall in those regions resulting in further drag reduction at the expense of a more complex system. Ideally, the suction needs to be only applied when a lift up or ejection is occurring from a low speed streak. To adapt this method to the wall layer would require additional geometrical constraints or some intelligence to determine when the suction should be applied. Thus, a more complex system would be necessary, but would require a reduced expenditure of energy.

Plans for Next Year's Research

The main plans for the coming year are to conclude the present phase of the research and present it at the IUTAM Symposium on *Structure of Turbulence and Drag Reduction* to be held at the Federal Institute of Technology in Zurich. The course of the research will be altered slightly in order to study the global effects of suction upon the turbulent boundary layer. This is considered important because so little is known about the effects of uniform suciton upon the structure of the near wall region. Only one recent work (Antonia, et al., J. Fluid Mech., 190, 217, 1989) has studied the effects of the suction upon the boundary layer structure and it included little detailed data. Although the present work indicated that the suc ion provided the expected trends in the bursting frequency and other statistics, the suction area was too small to examine an asymptotic state.

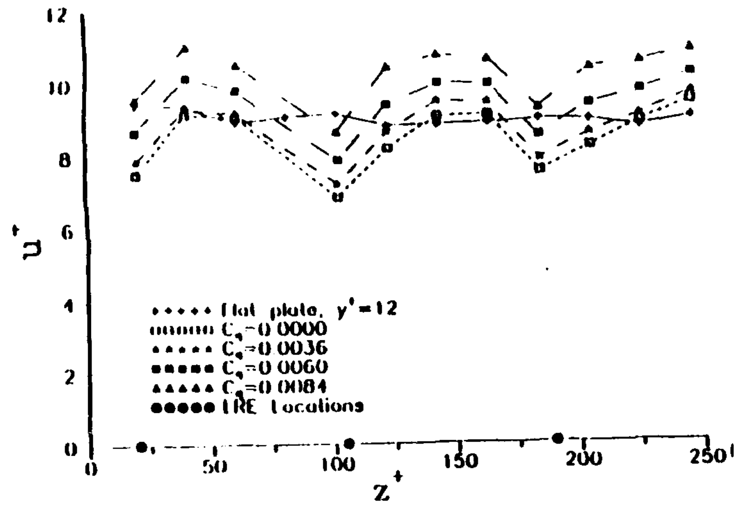

Figure 1. Spanwise velocity profiles for the flat plate, with the longitudinal roughness elements and suction.

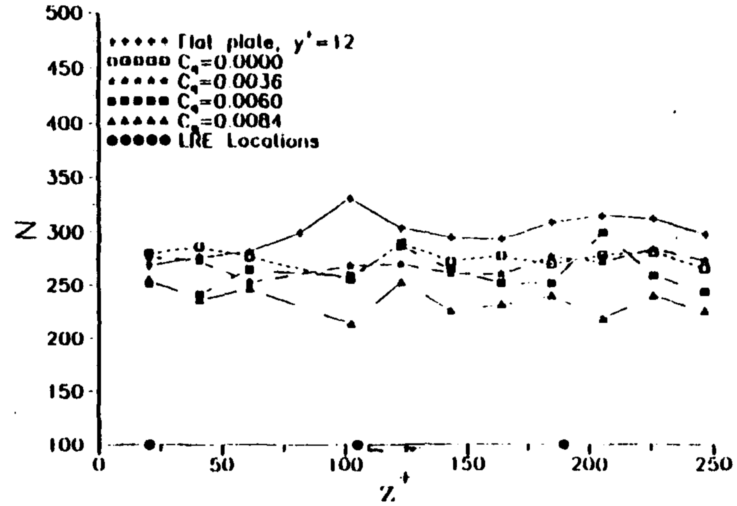

Figure 2. The number of detected LSSs with the longitudinal roughness elements and suction across the span.

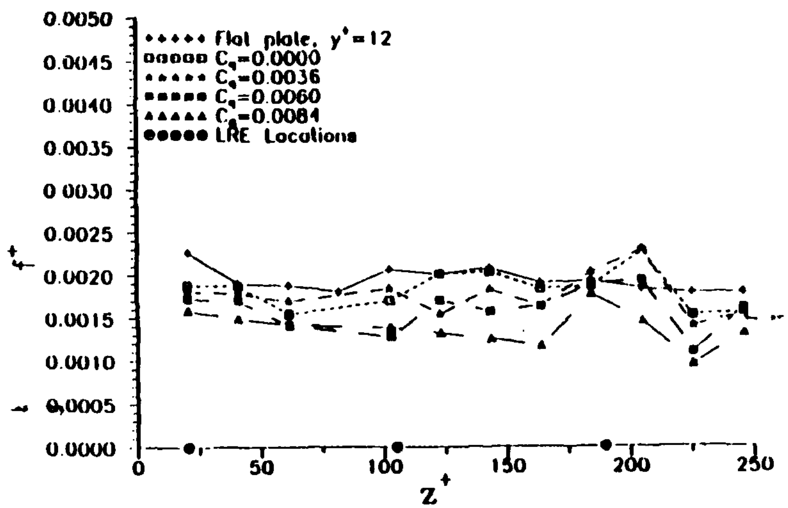

Figure 3. The VITA detection frequency with the longitudinal roughness elements and suction compared with the flat plate values.

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

   None

2. Technical Reports

   Ron F. Blackwelder, *Some Ideas on the Control of Near-Wall Eddies*, AIAA-89-1009.

   R. F. Blackwelder and J. B. Roon, *The Effects of Longitudinal Roughness Elements Upon the Turbulent Boundary Layer*, AIAA 88-0134.

3. Presentations

   Ron F. Blackwelder, "Some Ideas on the Control of Near-Wall Eddies", Invited paper at the AIAA 2nd Shear Flow Conference, Tempe, AZ, March 13-16, 1989.

   J. B. Roon and R. F. Blackwelder, "Modification of Turbulent Boundary Layers by Longitudinal Roughness Elements", American Physical Society, Division of Fluid Dynamics, 40th Anniversary Meeting, November 1987.

   J. B. Roon and R. F. Blackwelder, "The Effects of Longitudinal Roughness Elements Upon the Turbulent Boundary Layer", AIAA 26th Aerospace Sciences Meeting, January 1988.

List of Honors/Awards

R. F. Blackwelder, Elected Fellow of the American Physical Society

R. F. Blackwelder, Elected Associate Fellow of the American Institute of Aeronautics and Astronautics

R. F. Blackwelder, Keynote Address, International Symposium on Transport Phenomena, Tokyo, Japan

List of Participants

R. F. Blackwelder, Professor

J. B. Roon, Ph.D. student

F. Pray, M.S. student

CONTROL OF LAMINAR SEPARATED SHEAR LAYERS ON AIRFOILS

Principal Investigators: R. F. Blackwelder, R. H. Liebeck

Research Summary

Description of Scientific Research Goals

The primary goal of this research is a better understanding of the transitional instability mechanism which has a controlling effect on the extent of laminar separation bubbles occurring on airfoils operating at low Reynolds numbers ($R_c < 10^6$). With applications which include, for example, low speed unmanned aircraft, these airfoils experience an incremental drag penalty which becomes more severe as the extent of laminar separation region increases at lower R_c. Earlier transition has been shown to correlate with smaller bubbles and reduced drag. Results include a detailed experimental investigation of the low Reynolds number airfoil flowfield over a range of incidence, R_c and flow disturbance configurations such as free stream turbulence, acoustic disturbances and surface modifications. Ultimately, a greater knowledge of the separation bubble and instability mechanism would encourage the following:

1. Development of active control of the separated shear layer, such as local acoustic forcing, to accelerate transition within the separation bubble in cases where the drag penalty severely inhibits performance.
2. Increased confidence in low Reynolds number airfoil flowfield prediction methods which incorporate stability calculations for determining transition characterstics.
3. Design methods incorporating calculations based on more reliable prediction methods for this separated flow phenomenon resulting in more efficient (lower drag) airfoils.

Significant Results

Experimental work since this research was incorporated into the URI program last year represents a continuation of work previously funded by ONR under contract N00014-84-K-0500. Baseline boundary layer and drag data were obtained for a new 11.75" chord LA2573A airfoil model over a Reynolds number range from 235,000 to 500,000. These results successfully reproduced drag estimates from a 6" chord model where previous measurements were made at $R_c = 235{,}000$. Mean velocity profiles normalized with the boundary layer displacement thickness also collapsed data from both models at particular chord positions, as well as for different Reynolds numbers at positions upstream of transition. This result also supports transition as a controlling factor in the growth of the separation bubble and overall drag. Spectral analysis was made of the velocity signal inside the boundary layer to document the evolution of boundary layer instability and fluctuations through separation and transition for different airfoil incidence and Reynolds numbers. A spectral peak which develops in the separation region during transition has been found to correspond to the most amplified waves from a stability theory calculation. This calculation incorporated Falkner-Skan reverse flow profiles to represent the experimental flow. The measured spectral peak frequency follows the stability theory predictions as the airfoil chord length and Reynolds number were varied. Preliminary estimates of the amplification rates also agree with those predicted by stability calculations.

Tests have been conducted in which Wheeler vortex generators were applied to the airfoil model surface upstream of the laminar separation point. Results indicate that a decrease in drag as high as 30% from the clean airfoil is possible at Reynolds numbers below 400,000 with proper vortex generator sizing and spanwise spacing. The generators also showed a drag improvement over the case in which a standard grit roughness transition strip was used. Optimization of vortex generator size and spacing, and an analysis of drag sensitivity to airfoil incidence, remains to be investigated.

Plans for Next Year's Research

Experiments will investigate the spanwise coherence of the separated shear layer instability to determine the extent to which a local forcing disturbance might be used to accelerate transition over the entire airfoil surface. The effect of a local acoustic forcing and the addition of airfoil sweep will also be considered in examining the evolution and amplification of the separation bubble instability.

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

   None

2. Technical Reports

   None

3. Presentations

   None

List of Honors/Awards

R. H. Liebeck, McDonnell Douglas Fellow

List of Participants

R. F. Blackwelder, Professor

R. H. Liebeck, Adjunct Professor

P. J. LeBlanc, Ph.D. student

Mark Emanuelli, Undergraduate Assistant

David Herriot, Undergraduate Assistant

Scot Hutcherson, Undergraduate Assistant

Michael Kerho, Undergraduate Assistant

CONTROL OF THE LARGE-SCALE FEATURES IN TURBULENT MIXING LAYERS

Principal Investigator: F. K. Browand

Research Summary

Description of Scientific Research Goals

The broad goal is the explore the requirements for the control of turbulent shear flows. Control is effected by introducing perturbations which exert influence upon the underlying (turbulent) vortex structure. The turbulent mixing layer has been chosen as a candidate flow, and the response to a variety of imposed excitations will be investigated. Experimental results will be compared with numerical solutions of various evolution-equation models. These equations are simpler than the Navier-Stokes equations, yet hopefully contain the essential features needed to describe the large- scale flow evolution. The connection between experiment and theory will provide a strong predictive capability for the exploration of control strategies.

Significant Results

Perturbations can be applied at the origin of the mixing layer by means of acoustic forcing. One excitation of interest is periodic in time and periodic across the span of the flow. Wave lengths and periods are comparable to the streamwise spacing of developing vortices and their average passage period, respectively. Other excitations are designed to produce discrete space-time vortex structure; for example, vortex pattern imperfections or dislocations. The motion and development of pattern imperfections is a central comparison with evolution equation models.

We have constructed and tested an array of speakers designed to provide acoustical excitation. Sixteen small dynamic speakers are arranged in a linear array across the wind tunnel ceiling directly above the splitter plate trailing edge (origin of mixing layer). All speakers are operated at constant amplitude, but the phase of any speaker can be varied. A variety of spanwise modes can be generated by simply switching the phase of various speakers between the two states 0 degrees and 180 degrees. Using a three microphone array, and an automated data acquisition system, the acoustic field in the cross section of the plate trailing edge has been surveyed. The results show that low wave number modes are easily excited at the plate trailing edge because these waves are near resonance at frequencies of 1 kHz or less. The higher standing wave modes (corresponding to more than four wave lengths across the span) are more difficult to excite. The forcing signal decays exponentially away from the wind tunnel ceiling and, at the central plane, the acoustic field is again dominated by lower modes. The presence of unwanted lower modes in this case is probably due to slight differences in amplitude of the different speakers.

Vortex pattern imperfections, which appear similar to dislocations in a regular crystal lattice, arise naturally in the nonlinear evolution of the mixing layer flow. Such dislocations are the major pattern defect and are important in understanding the transition process. We have documented the distribution of dislocations across the span, and have also counted the number of dislocations in a suitable space-time area as the flow develops downstream. These numbers are being compared with the predictions from our nonlinear evolution-equation model.

Dislocations which arise naturally cannot be studied in detail because they appear randomly in space and time. We have therefore perfected a more sophisticated forcing procedure to produce artificial imperfections in the vortex patterns. Pulse trains containing two frequencies differing by about 10% are produced by computer. The pulse trains are output to various speakers across the span via shaping networks and amplifiers. These differing frequency acoustic pulse trains produce velocity perturbations at the origin of the flow and impose differing separations upon the growing vortex structure. The dislocations which form from each application of the pulse train are highly reproducible. (Only small amounts of input forcing are required.) The flow field surrounding the dislocation can be constructed by utilizing many identical pulses. In this way, very high spatial resolution can be achieved with a small number of measuring probes. We are presently using three hot wire probes and twenty pulses for a total of sixty span measurement stations surrounding the defect.

The principal preliminary result is that a dislocation-once-formed is a virulent structure. It steepens dramatically while travelling downstream and nucleates additional defects in the immediate vicinity. The evolution equation model displays a similar behavior, and we are quite encouraged by this qualitative agreement. The results are discussed in publication (b), and the companion publication by Yang, Huerre, and Coullet.

Plans for Next Year's Research

Our plan for the coming year is to study the evolution of a variety of defect structures in more detail. We would like to obtain a global picture of the defect evolution. This will include quantitative measures of defect motion within the pattern, and the number and placement of additional defects which are nucleated. These results will be compared with the evolution equation model. We will also begin to measure various components of the evolving vorticity field as well as the velocity fluctuations.

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals/Conference Proceedings

   (a) F. K. Browand and C.-M. Ho. "Forced, Unbounded Shear Flows," *Nuclear Physics B*, (Proc. Suppl.) 2 1987 *International Conference on the Physics of Chaos and Systems Far from Equilibrium*, M. Duong-Van, editor, North Holland.

   (b) F. K. Browand and S. Prost-Domasky. "Experiment on Pattern Evolution in the 2-D Mixing Layer," *New Trends in Nonlinear Dynamics and Patterning Phenomena: The Geometry of Non Equilibrium*, NATO ASI Series B, P. Coullet and P. Huerre, editors, New York/London Plenum, 1989.

   (c) F. K. Browand and S. Prost-Domasky, "A Technique for Acoustic Excitation of Separated Shear Flows: Preliminary Results," *Nonlinear Interaction Effects and Chaotic Motions* – Volume 7, M. Reischman, M. Pardoussis, R. J. Hansen, editors, ASME Winter Meeting, Chicago (Book no. G00447).

2. Technical Reports

   None

3. Presentations

   F. K. Browand, "Forced, Unbounded Shear Flows," *The Physics of Chaos and Systems Far from Equilibrium*, Monterey, California, January 11-14, 1987.

   F. K. Browand, "Experiments on Pattern Evolution in Mixing Layers," *New Trends in Nonlinear Dynamics and Patterning Phenomena: The Geometry of Non Equilibrium*, Cargese, France, August 2-12, 1988.

   F. K. Browand, "Pattern Evolution in Mixing Layers," *International Congress of Theoretical and Applied Mechanics*, Grenoble, France, August 21-27, 1988.

   F. K. Browand, "A Technique for Acoustic Excitation of Separated Shear Flows: Preliminary Results," ASME Winter meeting, Chicago, Illinois, November 27-December 2, 1988.

List of Honors/Awards

F. K. Browand, Elected Fellow of the American Physical Society, November 1988.

List of Participants

F. K. Browand, Professor

S. Prost-Domasky, Research Assistant

DIRECT NUMERICAL SIMULATIONS OF FLOW CONTROL

Principal Investigator: J. A. Domaradzki

Research Summary

Description of Scientific Research Goals

The principal goal is to simulate numerically specific fluid flows of interest to the Navy in order to better understand their physics, in particular those physical features which can be effectively controlled by either external disturbances or boundary conditions.

Two types of flows were chosen for investigation: free convection and boundary layer flow over a concave surface. The understanding of convective flows is important in the task of designing heat pipes, heat exchangers, and cooling of electronic equipment. The fluid flow over a concave surface develops a regular pattern of Görtler vortices which can serve as a general model of counter- rotating vortices encountered in other transitional and turbulent boundary layers. The behavior of these vortices is important in many practical situations; for example, determining efficiency of turbine blades, drag on objects moving in fluids, etc.

The goals of this research are to develop numerical codes capable of simulating these phenomena, investigate the possibility of influencing heat transfer through modification of boundary conditions, describe energy transfer in the transitional and turbulent boundary layers over concave walls, and prepare new methods of delaying transition in such flows.

An additional research topic, partially supported by the ONR-URI during the last year, involved an investigation of energy transfer in numerically simulated isotropic turbulence. This work was done in collaboration with Dr. R. S. Rogallo of NASA-Ames and was also a part of the Summer Program 1989 of the Stanford/NASA-Ames Center for Turbulence Research.

The goals of the energy transfer analysis are to better understand dynamics of interactions between large and small scales of turbulence. The clear understanding of these interactions is necessary in order to assess how small scales of turbulence can be influenced by modifying/controlling only large scales which are more amenable to experimental manipulation than the small scales.

Significant Results

In the first year of this effort we were able to obtain new physical results in the area of convection. Our rapid progress in this area was possible because we were able to use a numerical code which was developed previously under contract from DOE to simulate convection with an imposed mean shear. We have performed a number of numerical simulations of the convection between two rigid, horizontal plates with nonuniform-temperature boundary conditions at the lower plate. The boundary conditions were chosen to excite n pairs of counter-rotating convective rolls. For given horizontal size of the computational domain, runs with different values of the parameter n were performed. It was shown that different numbers of convective rolls could be accommodated in the same physical domain. In particular, it was possible to generate through the nonuniform-temperature boundary conditions rolls with sizes significantly different from the size of rolls encountered in natural convection at the same Rayleigh number. The control over the size of the convective elements allowed about 15-20% heat transfer increase as compared with the case of natural convection.

In the area of numerical simulations of Görtler vortices, the first year effort was devoted to the modification of the flat plate boundary layer code to include curvature effects, and the modification of the pressure boundary conditions in the full time-splitting scheme to eliminate the velocity divergence errors.

In the last year the numerical code has been implemented on the Cray X-MP at the San Diego Supercomputer Center. Through a number of separate proposals to the SDSC, a total of eighty-seven hours of CPU time were obtained to perform the numerical simulations. About thirty hours have been used so far.

The following results have been obtained in our studies to date. The growth rates of unstable Görtler vortices obtained from the linear stability theory were compared with the growth rates predicted by the Navier-Stokes solver. The results agree to four digits after the decimal point. This level of accuracy is less than that attained by divergence-free codes and comparable to the accuracy obtained by using the full time splitting schems. Thus it seems that various modifications of the pressure boundary conditions in the full time-splitting scheme designed to reduce the velocity divergence errors do not improve the overall accuracy of the code.

Simulation of the Görtler flow were performed with different initial conditions for the velocity field (a random initial condition and an initial condition composed of the most unstable mode of the linear theory). The results were compared with the experiments of Swearingen and Blackwelder (JFM 182, 255 (1987)) and a good agreement was obtained in the laminar regime. At the present time we are probing the beginning of the transitional regime. The numberical simulations properly reproduce all qualitative features of this regime as observed in the experiments.

The most difficult, technical problem encountered in these simulations was related to a need to adequately resolve two boundary layers with different thicknesses induced by the counter-rotating vortices: the thick boundary layer in the upwash region and the thin boundary layer in the downwash region. The mesh points in the direction normal to the plate have to be carefully distributed and the minimum resolution requirements for accurate simulations are 128 mesh points in the vertical.

Regarding the topic of the energy transfer in isotropic turbulence studied during the Stanford/Ames Summer Program 1989, detailed measurements were made of energy transfer among the scales of motion in incompressible turbulent fields at low Reynolds numbers generated by direct numerical simulations. It was observed that the transfer resulted from triad interactions that were nonlocal in k (wavenumber) space, but the energy always transferred locally. The ONR-URI support was used to investigate the energy transfer at high Reynolds numbers in the framework of the Eddy-Damped Quasi-Normal Markovian (EDQNM) approximation. The EDQNM theory predicts the same transfer mechanism in the inertial range that is observed at low Reynolds numbers (i.e., predominantly local transfer caused by nonlocal triads). Coupling between very large and very small scales of turbulence revealed by our analysis suggests that it may be possible to influence dynamics of the small scales by active control/modification of the large scales.

Plans for Next Year's Research

Next year's effort will be devoted principally to applying a modified boundary layer code to investigate transition to turbulence in the Görtler flow. In particular we plan to use the Reynolds stress and energy equations to assess the importance of different physical effects (inflectional velocity profiles in spanwise and normal direction, three-dimensional disturbances, low speed streaks, etc.) in the transition to turbulence.

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

   Domaradzki, J. A., "Heat Transfer Enhancement in Rayleigh-Bénard Convection" accepted for publication *Int. J. Heat Mass Transfer*, April 1989.

   Domaradzki, J. A. and Rogallo, R. S., "Local Energy Transfer and Nonlocal Interactions in Homogeneous, Isotropic Turbulence" to be submitted to *Phys. Fluids*.

2. Technical Reports

   None

3. Presentations (invited seminars)

   "Local Energy Transfer and Nonlocal Interactions in Isotropic Turbulence"

   - University of Houston, Houston, Texas, April 27, 1989
   - National Center for Atmospheric Research, Boulder, Colorado, May 19, 1989

List of Honors/Awards

None

List of Participants

J. A. Domaradzki, Assistant Professor

Liu Wei, Ph.D. student (supported by Powell Foundation Grant as part of institutional support in conjuction with the ONR-URI contract).

CONTROL OF ENTRAINMENT IN CONFINED SHEAR LAYERS

Principal Investigator: C.-M. Ho

Research Summary

Description of Scientific Research Goals

The control of mixing processes between two fluids is crucial in improving the efficiency of many engineering applications such as combustors, rocket engines, chemical lasers and heat exchangers. Since mixing and entrainment are dominated by the unsteady evolution of coherent structures in the shear layer between the streams, active and passive forcing techniques have been developed to control this evolution. A large increase in entrainment has been achieved in some cases involving active forcing in shear flows and passive and active forcing in asymmetric jets. However, these studies were made in unconfined flows while almost all engineering applications are confined. Confinement can significantly alter the development of coherent structures in shear layers, particularly in cases where the shear layer reattaches to a wall such as in sudden duct expansions and dump combustors. Thus, the goals of the present experimental research are to understand the effect of confinement on forced shear layers.

Significant Results

(i) Facility and Instrumentation

A new multi-configuration water channel facility has been built to study the effects of active and passive control on confined three dimensional reattaching shear layers. After testing several flow systems, this versatile channel is in full operating condition. Although the configuration can be varied from a single-sided backward facing step to a fully asymmetric rectangular sudden expansion, experiments to date have concentrated on a 2:1 aspect ratio rectangular jet which undergoes a sudden expansion with uniform step height (h). The use of a rectangular jet of small aspect ratio rather than an axisymmetric or plane confined jet comprises the passive forcing of the shear layer. Figure 1 shows a schematic of this configuration.

Two diagnostic systems have been developed to study this flow. Hydrogen bubble flow visualization is used to qualitatively examine the dynamics of large vortex rings in this configuration and to study the structure of the reattachment region. Two-component laser doppler velocimetry is used to quantitatively study the steady state flow. Data acquisition is entirely computer controlled.

(ii) Flow-Field Characteristics

Preliminary visualization studies reveal that a large asymmetric vortex ring, created by impulsively starting the rectangular jet, experiences rapid breakdown as a result of the confining effects of the walls. Where a free vortex ring of this shape would undergo several axis switchings as a result of self induction before decaying, the confined ring is slowed and distorted by the walls, as well as the attendant image vortices, and breaks down soon after a single axis switch. Since the development of the shear layer surrounding a rectangular jet can be dominated by coherent vortex structures resembling such a starting vortex, these results suggest that shorter reattachment lengths and high mixing levels can be expected in the minor axis plane under steady state conditions.

LDV measurements confirm this picture of the flow structure and, in fact, reveal that no time-averaged recirculation zone is found in the minor axis plane. Instead, a region of slightly positive mean flow with moderate fluctuations is found downstream of the jet. This is a new and significant finding. In order to compensate for the streamwise mass flux, there must exist circumferential mass transfer. In other words, in the region immediately after the step, which is usually a fuel rich region in a ram jet, mixing can be greatly enhanced. These results demonstrate that passive forcing in the form of jet asymmetry can have a significant effect on the flow field of a confined shear layer.

There is strong recirculation, however, in the major axis plane. This is shown in Figure 2 where the time-averaged streamwise velocity is plotted versus downstream position at a distance of 0.125 inches from the end of the minor axis, and 0.2 inches from the end of the major axis. The recirculation zone length is 10 step heights, which is slightly longer than expected for a step Reynolds number of 12,000.

Plans for Next Year's Research

(i) The lack of a recirculation zone in the minor axis plane is an extremly important finding in the control of confined shear layers. We will concentrate our effort in examining this phenomenon from the deterministic structure point of view.

(ii) A rotating valve has been installed recently in order to study the effect of active global forcing on the shear layer recirculation regions. Preliminary results indicate futher significant effects on the flow field structure.

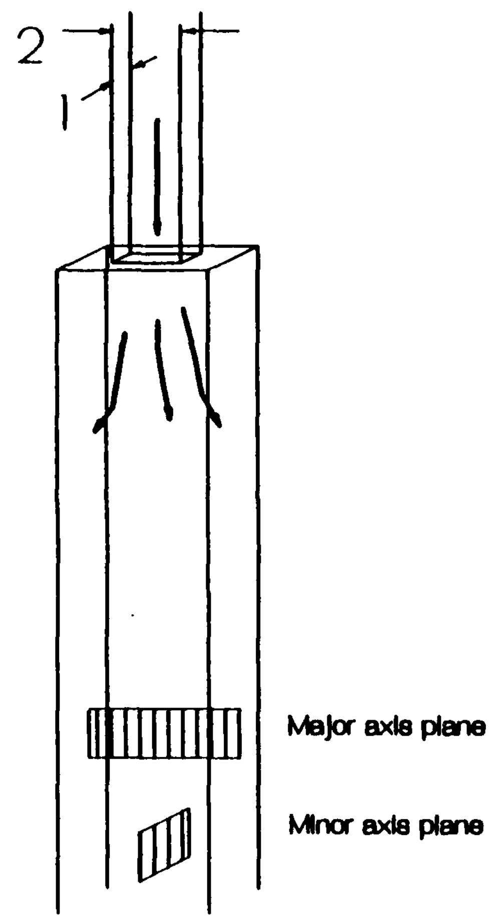

Fig 1: Rectangular sudden expansion

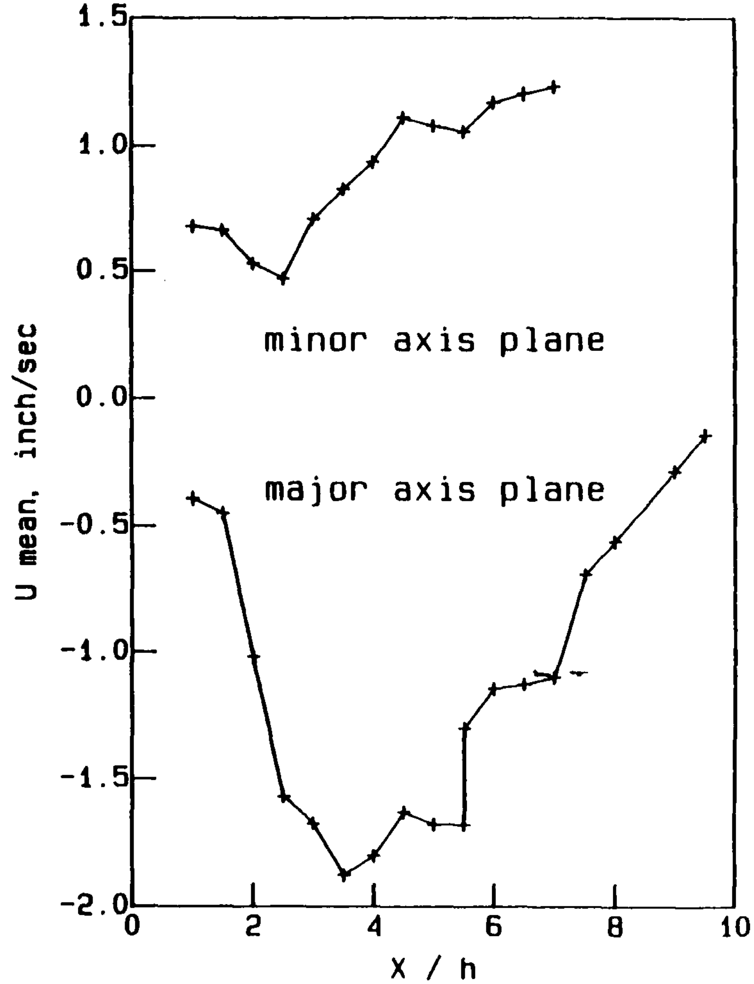

Fig 2: Near wall velocities

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

   C.M. Ho, T. Austin and J.R. Hertzberg "Entrainment of 3-D Shear Layers". Paper accepted by the Fourth Asian Congress of Fluid Mechanics, Hong Kong, 1989.

2. Technical Reports

   None

3. Presentations

   J.R. Hertzberg and C.-M. Ho "Vortex Dynamics in an Isothermal Dump Combustor". Poster Session at the Twenty-Second Symposium (International) on Combustion, University of Washington, Aug. 14-19, 1988. Abstract published in Symposium Abstract book, Combustion Institute 1988.

   J.R. Hertzberg and C.-M. Ho "Vortex Dynamics in a Rectangular Sudden Expansion". Paper presented at the Forty-First Annual Meeting of the Division of Fluid Dynamics, American Physical Society. Abstract published in *Bull. A.P.S.* Vol. 33, no. 10 (1988), p 2233.

List of Honors/Awards

None

List of Participants

Ho, Chih-Ming, Professor

Jean Hertzberg, Research Associate

Mike Bailey, Undergraduate Assistant

Chris Niestepski, Undergraduate Assistant

Scott Reader, Undergraduate Assistant

THEORETICAL UNDERPINNINGS: AMPLITUDE AND PHASE DESCRIPTIONS OF COHERENT STRUCTURES

Principal Investigators: P. Huerre and L. G. Redekopp.

Research Summary

Description of Scientific Research Goals

The dynamics and control of coherent structures in free shear flows such as mixing layers and wakes is to be analyzed in terms of a suitable superposition of interacting instability waves subjected to external forcing. Rational analytical models of the global dynamics are to be obtained in terms of nonlinear evolution equations governing either the amplitude or the phase of the wave. The spatio-temporal dynamics of the structures under both natural and controlled conditions will be studied numerically on both types of models. Efficient flow control strategies are to be developed to alter the long-range interactions between structures.

Streamwise vortices are known to play a crucial role in the transition from laminar to turbulent flow in boundary layers. Analytical and numerical studies of the development of Görtler vortices on a concave plate are to be conducted to arrive at a fundamental understanding of the primary instability evolution and of the development of secondary instabilities.

Significant results

Progress has been made in 4 distinct areas as summarized below.

(1) A phase dynamics description of the evolution of Kelvin-Helmholtz vortices in stratified mixing layers has been rationally derived from the basic governing equations in the viscous critical layer limit [Huerre (1987)]. The combined translational and Galilean invariance of the initial problem has been shown to give rise to strong coupling between the structures and a large-scale, horizontal, velocity field. Two types of phase instabilities have been identified. A modified Eckhaus instability can occur as local "compressions" and "expansions" of the vortex array are induced along the stream. This mechanism, which is primarily one-dimensional, could account for phase decorrelations between structures. The second type of phase instability is three-dimensional in character, the most amplified disturbance being obtained at a wavenumber inclined to the flow direction. Finally, in the region of stable configurations, anisotropic phase waves may propagate on the vortex structures.

(2) Concurrently, Mr. Ruixin Yang, a Ph.D. student supported by the ONR core program, has carried out a numerical study of a two-dimensional model of pattern evolution in mixing layers [Yang, Huerre, and Coullet (1988)]. This investigation is a joint collaboration with F. K. Browand who is performing companion experiments. In contrast with the previous case, the field equation governing the amplitude evolution of the waves has been postulated.

The invariance properties of the problem, together with the presence of shear, place strict constraints on the nature of the linear operator, as observed in the context of convection by Swift and Hohenberg at Bell Laboratories. Interactions with the large scale field have been inferred from the asymptotic model described above under item (1).

This non-potential pattern evolution model has been shown to reproduce many of the features observed in mixing layers. Experimentally one observes a downstream evolution toward an ordered quasi-two-dimensional pattern. Imperfections in the pattern lead to the formation of dislocations. If the initial state is chosen to be turbulent, the model results reveal a similar behavior: random input gives rise to organized spanwise vortices in the long-time evolution, with the presence of dislocations. When a mixing layer is acoustically perturbed at slightly different frequencies along the span, controlled dislocations can be produced experimentally which generate additional defects further downstream. Dislocation pairs are also produced in the model by suitably choosing the initial state. The results of numerical simulations indicate that new defects are then nucleated [see Fig. 1]. The last type of input which has so far been analysed for the model involves noisy, random, infinitesimal perturbations superimposed on a perfect two-dimensional array of vortices. Remarkably, dislocations are found to be spontaneously generated in the flow as a result of intrinsic phase instabilities [see Fig. 2]. This result may provide an important clue to the mechanism of dislocation nucleation in shear flows.

(3) A rational model for the amplitude evolution of coherent structures in confined mixing layers has been derived for both two-dimensional and three-dimensional motion. The model represents a significant reduction of the full equations of motion in that the cross-stream structure is separated from the streamwise and transverse variations. The resulting model is an integro-partial differential equation in one- or two-space coordinates plus time. The model accounts for interactions between all unstable wavenumbers. Thus, transfer of energy to larger scales and vortex pairing are captured by the model. This is in contrast to a phase dynamics description which focuses on the large scale interactions between structures whose amplitude is entirely slaved to phase variations. The nature of the finite-amplitude dynamics described by the present model is found to depend on both the structure of the critical layer encompassing the inflection point of the basic velocity profile and the super-criticality of the profile. The space-time scalings implicit in the two-space dimensional model are consistent with Squire's transformation of the plane wave dispersion relation. A numerical code is currently being developed to study the response of the model system to controlled inputs.

(4) The linear evolution of wave packets in boundary layers on a concave wall with suction has been studied analytically and numerically. The application of suction removes technical difficulties associated with the growth of the boundary layer. The basic velocity profile remains unchanged in the streamwise direction. It has been shown numerically [Park and Huerre (1988)] that the impulse response of the flow takes the form of a wavepacket which is convected downstram. Thus, the Görtler instability is convective in character and it is expected to be extremely sensitive to external perturbations. This result has been confirmed by a study of the dispersion relation in the complex frequency plane: there are no saddle points at finite distance. A nonlinear evolution model of the Ginzburg-Landau variety has been derived in the vicinity of the critical Görtler number. The cubic-nonlinearity was found

to be destabilizing. Görtler vortices, therefore, appear via a subcritical stationary bifurcation. A full numerical code has been developed to characterize the finite-amplitude branch away from threshold when the motion is assumed to be uniform in the streamwise direction. It has been confirmed that the bifurcation is subcritical. As perturbations grow away from the basic state to reach the finite-amplitude solution, the mean velocity profile exhibits extremely strong inflection points. In the presence of streamwise fluctuations these would be the site of Kelvin-Helmholtz instabilities.

Plans for Next Year's Research

Research in the above four areas will be actively pursued.

Preliminary analytical investigations of the motion of dislocations have been undertaken. In the absence of a large-scale vertical vorticity field, one can appeal to available results in anisotropic nematic liquid crystals. The velocity of dislocations is then linearly proportional to δq. Here δq is the departure of the background wavenumber from the value at which dislocations are stationary. We would like to verify this scaling law numerically and determine the effects of the vertical vorticity field. Perturbation analyses will be used to obtain the dominant contribution from non-potential effects. Coefficients appearing in the pattern evolution model will be calibrated by fitting the properties of the model to known linear and nonlinear stability characteristics. This will supply valuable information to compare the results of the model with the experiments. Concurrently, we shall characterize the main statistical properties of the turbulent regime in situations where defects are spontaneously nucleated (defect-mediated turbulence).

The amplitude evolution model will be used to study the response of the mixing layer to one- and two-dimensional disturbances. Vortex pairing and collective interactions will be studied using the one-space dimensional model. The two-space dimensional model will be used to study spanwise-varying inputs and comparisons with experimental observations by Browand will be made. the evolution model will then be used to explore forcing scenarios which either enhance or delay mixing layer growth and the level of three-dimensionality. A control theory for the one-space dimensional model will be initiated.

In the Görtler problem, the formulation needs to be generalized to include the secondary instability of Görtler vortices to streamwise dependent perturbations. It is important to determine if the finite-amplitude Görtler branch is always unstable to Kelvin-Helmholtz disturbances. Fortunately, the time scales pertaining to the development of Görtler vortices and to the Kelvin-Helmholtz mechanism are well-separated. We intend to take advantage of this feature to set up a multiple scale analysis of the development of Kelvin-Helmholtz waves on a slowly-varying Görtler field. This study will provide valuable information on the dynamics of spatially-periodic, inflectional profiles.

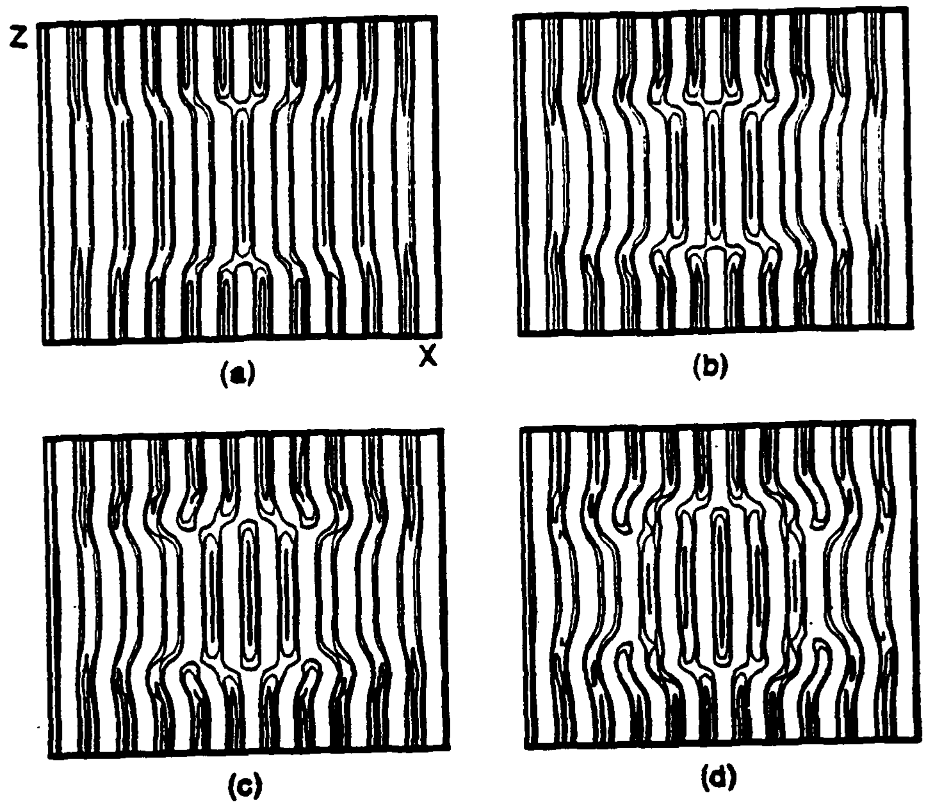

Figure 1. Nucleation of dislocations by dislocations.

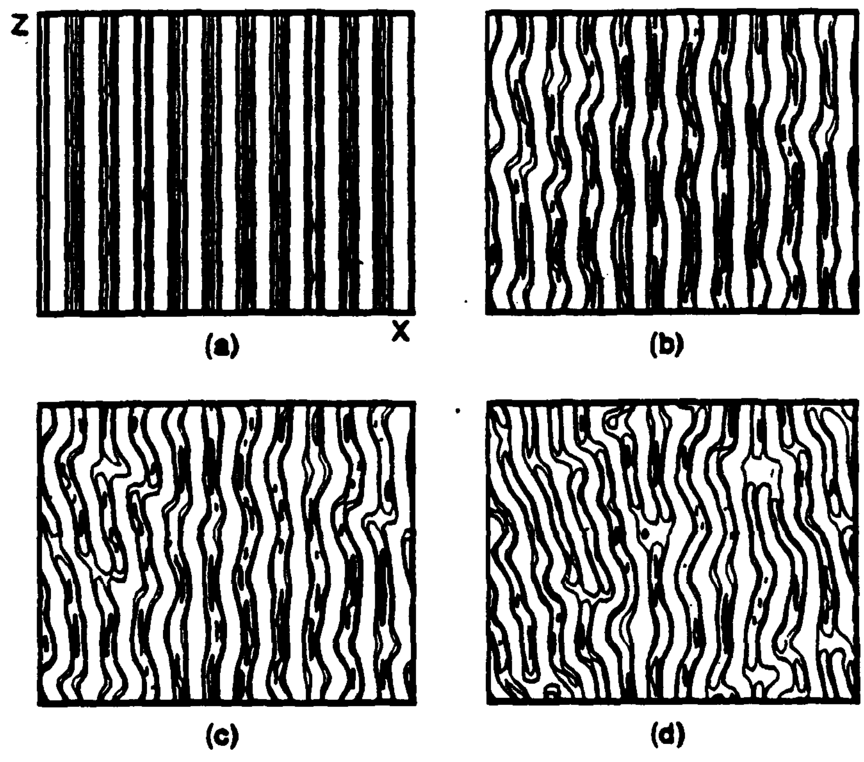

Figure 2. Nucleation of dislocations by phase perturbations.

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

Yang, R., Huerre, P., and Coullet, P. (1988). "A Two-Dimensional Model of Pattern Evolution in Mixing Layers." To appear in the proceedings of "New Trends in Nonlinear Dynamics and Pattern-Forming Phenomena: The Geometry of Non Equilibrium.: NATO ASI Series B, P. Coullet and P. Huerre, editors, New York/London: Plenum.

Huerre, P. (1987). "Evolution of Coherent Structures in Shear Flows: A Phase Dynamics Approach." Nuclear Physics B (Proc. Suppl.), 2:159.

Djordjevic, V. D., and Redekopp, L. G. (1989). "Nonlinear Stability Properties of Subsonic Mixing Layers with Symmetric Temperature Variations." accepted for publication in *Phil. Trans. of Roy. Soc. London.*

2. Technical Reports

Djordjevic, V. D., Pavithran, S., and Redekopp, L. G. (1989). "Stability Properties of Subsonic Mixing Layers." AIAA Paper No. 89-1020.

3. Presentations

Redekopp, L. G. (1989). "Stability Properties of Subsonic Mixing Layers." AIAA Second Shear Flow Conference, Tempe, AZ, March 12-16, 1989.

Park, D., and Huerre, P. (1988). "On the Convective Nature of the Görtler Instability." Bulletin of the American Physical Society, vol. 33, p. 2252.

Yang, R., Huerre, P. and Coullet, P., (1988). "Models of Pattern Formation and Dislocations in Free Shear Flows." Bulletin of the American Physical Society, vol. 33, p. 2256.

Huerre, P. (Dec. 21, 1988). "Structures coherentes et ondes d'instabilite dans le ecoulements cisailles." Seminar, Department of Mechanics, Ecole Polytechnique, Palaiseau, France.

Huerre, P. (Jan 9-11, 1989). "Hydrodynamic Instabilities in Free Shear Flows: spatio-temporal descriptions." Invited series of lectures, DARPA/URI Winter School in Fluid Dynamics, Institue for Nonlinear Science, University of California, San Diego.

Huerre, P. (May 3, 1988). "Nonlinear Dynamical Systems", Joint ONR/AFOSR Colloquium on Active Control and Turbomachinery Hydroacoustics, Washington, D.C., May 3-4, 1988.

Huerre, P. (May 2, 1988). "Order and Disorder of the Large Scales in Free Shear Flows", Seminar, Naval Research Laboratory, Washington, D.C.

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

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

Huerre, P. (Jan. 22, 1988). "Large-Scale Dynamics in Open Flows", Nonlinear Science Seminar, University of California, Santa Barbara.

Huerre, P. (Dec. 16-22, 1987). "Spatio-temporal Evolution of Coherent Structures." Invited lecture, Second International Workshop on Instabilities and Nonequilibrium Structures, Universidad Federico Santa Maria, Valparaiso, Chile.

Huerre, P. (Nov. 24, 1987). "Spatio-Temporal Dynamics in Free Shear Flows", Invited Lecture, 40th Annual Meeting of the Division of Fluid Dynamics, Eugene, Oregon, Nov. 22-24, 1987.

Asano, H., Huerre, P. and Redekopp, L. G. (1987). "Finite Amplitude, Three- Dimensional, Kelvin-Helmholtz Instability Waves in Bounded Shear Layers." 40th meeting of the Division of Fluid Dynamics of the American Physical Society, November 1987, Eugene, Oregon.

Huerre, P. (Sept. 11, 1987). "Dynamique des Structures Coherentes et Ondes d'Instabilite dans les Ecoulements Cisailles", Special Seminar, Universite d'Orsay, Paris, France.

Huerre, P. (Aug. 20, 1987). "Heuristic Introduction to Chaos", Miniworkshop, China Lake Naval Weapons Center, California.

Huerre, P. (July 23, 1987). "Amplitude and Phase Evolution of Coherent Structures in Free Shear Flows", invited talk, American Mathematical Society Conference on "The Connection between Infinite Dimensional and Finite Dimensional Dynamical Systems", University of Colorado at Boulder.

Huerre, P. (Mar. 18, 1987). "Hydrodynamic Instabilities in Open Flows: A Bird's Eye View", Workshop on "Propagation in Far From Equilibrium Structures", Les Houches, France, March 11-18, 1987.

Browand, F. K., and Huerre, P. (Jan. 13, 1987). "The Structure of the Turbulent Mixing Layer", with F.K. Browand, International Conference on the Physics of Chaos and Systems Far from Equilibrium, Monterey, California, January 11-14, 1987.

Huerre, P. (Oct. 24, 1986). "Phase Dynamics of Large Structures in Benard Convection and Stratified Mixing Layers", Applied Mathematics Colloquium, University of Arizona, Tucson.

List of Honors/Awards

P. Huerre, May 1989, TRW Award for Teaching Excellence, School of Engineering, USC.

L. G. Redekopp, Elected Fellow of the American Physical Society, November 1987.

List of Participants

P. Huerre, Professor

L. G. Redekopp, Professor

H. Asano, Ph.D. student

D. Park, Ph.D. student

R. Yang, Ph.D. student (not supported by ONR-URI contract)

PHASE CONTROL OF VORTEX STRUCTURES IN SHEAR FLOWS

Principal Investigator: T. Maxworthy

Research Summary

Description of Scientific Research Goals

Persistent patterns of vortex structures emerge as a result of instability processes in many shear flows. These patterns exhibit a high degree of spatial coherence and determine the characteristic scales which dominate the turbulent energy specturm. One approach toward control or influence of the turbulent scales is through external control of the phase relationships between vortex structures on length scales which encompass many individual features. The goal of this task is to produce laboratory flows containing an extensive pattern of vortex structures driven by a common instability mechanism, and then to explore the response of these patterns to control inputs which principally influence the phase relationship within the pattern. In particular, we seek to clarify the response of vortex patterns to phase disturbances which are incommensurate with the underlying instability scale.

Significant Results

The first of two pieces of apparatus to study problems of vortex dynamics and control has been built and placed in operation. It has been designed to complement the numerical work of Professor Domaradzki and the theoretical work of Professor Huerre on unsteady Görtler instability. Here we study the controlled spin-down of a rotating cylinder initially containing a fluid in solid-body rotation. As the boundary layer on the concave cylinder surface grows it becomes unstable to a temporally growing Görtler instability. The flow can be observed in a number of ways: initially by reflection of external lighting from aluminum flakes suspended in the flow and by observing a cross-section of the evolving flow using a sheet of laser light projected normally to the cylinder surface. In the later approach, velocity measurements can be made using the "laser speckle" technique. Visualisation is enhanced by placing the cylinder in a square box filled with refraction-index-matching fluid to remove distortion created by the cylinder. A number of experiments have been run in which the cylinder was brought rapidly to rest and the results correlated using a simple extension of the original Görtler theory. Following the generation of the initial instability, at a well defined wavelength, the vortex pattern undergoes a rapid and, as yet, ill-understood transition to a state with approximately double the original vortex spacing. This process includes the appearance of dislocations in the vortex rings and a sudden amalgamation of vortices of the same sign. This wavelength-doubling process continues until the cylinder is filled with a very disturbed turbulent flow containing discernable azimuthal vortices. Preliminary experiments on the slow spin-down of the cylinder show, as found in the work of Weidman, that stability is enhanced and that the vortex "doubling" process is less violent. This is presumably due to the stabilizing effect of system rotation on the generation of the vortices, a phenomenon discussed recently by Anderson and a group of the Royal Institute of Stockholm for the case of rotating, Poiseuille flow in a curved channel (to appear in JFM).

A second laboratory experiment is currently under construction. It consists of two concentric, rotating cylinders with working fluid in the annular gap between them. The inner cylinder is machined with a wavy surface of known wavelength and amplitude. This provides a perturbation to the unstable Taylor flow that is incommensurate with that which would occur in its absence. The adjustment of the flow to this boundary condition has been the subject of theoretical work by Professor Huerre and his predictions will form the preliminary basis for our interpretation of the results.

Plans for Next Year's Research

With ONR sponsorship we have developed methods to automatically track small, neutrally-bouyant particles in complex flow fields. These techniques and those of laser speckle velocimetry are ideal for the study of the flow we are considering here. The coming year will concentrate on velocity measurements within the unsteady Görtler flow experiment and the attempt to understand the complex vortex interactions and reorganizations during the transition to larger vortex scales. The spatial-modulated, circular Couette flow apparatus will be used to explore the characteristics of the system and to observe, if possible, the states predicted by the Huerre analysis. Here also, speckle velocimetry will be used to characterize the velocity field of these flows and their temporal evolution.

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

   None

2. Technical Reports

   None

3. Presentations

   None

List of Honors/Awards

T. Maxworthy, Smith International Professor of Mechanical and Aerospace Engineering

List of Participants

T. Maxworthy, Professor

E. Ikeda, Ph.D. student

J. Wiggert, Ph.D. student

MATHEMATICAL ANALYSIS OF THE NAVIER STOKES EQUATIONS

Principal Investigator: S. S. Sritharan

Research Summary

Description of Scientific Research Goals

This research involves three inter-related topics in turbulence theory: (i) investigation of the structure of attractors and invariant manifolds; (ii) global unique solvability of viscous flow past unbounded geometries; and (iii) optimal control theory. Research is being performed to understand the functional attractors characterizing three dimensional viscous motion. We study both the conventional as well as the regularized Navier Stokes equations in this respect. The attractor of a turbulent flow may be of fractional dimension. It is therefore of interest to find finite dimensional manifolds ("surfaces") which contain the attractor. If such manifolds are invariant with respect to the time evolution of the hydrodynamic solution operator, then the coordinates of these manifolds would provide an efficient computational tool. The fundamental element in the mathematical analysis of shear flows is the global unique solvability theorem. This result would be basic to numerical analysis, attractor theory, and also to optimal control theory. There are global unique solvability theorems for viscous flow in bounded domains (at least for sufficiently low initial enstrophy.) Much less is known regarding viscous flow in *channel-type configurations*. One of our major goals is to investigate this problem for unbounded channel geometries.

The central topic of our research is of course, the control of fluid flows. We have made a major breakthrough in developing optimal control theory for a certain class of hydrodynamic situations.

Significant Results

A. Mathematical theory of channel flows. This is a joint research with Professor J. G. Heywood of the University of British Columbia. We have proved the existence and uniqueness of two-dimensional, time-dependent, viscous flow past unbounded configurations with outlets which open at infinity. The two dimensional problem is particularly difficult since the finite energy solutions cannot carry flux through the outlets. The task was to find a flux carrying infinite energy vector field.

B. Optimal control theory of viscous flows. We have devloped a theory for driving a given flowfield to a desired flow field by means of control forcings. Existence of an optimal solution minimizing a suitable cost quadratic functional is established. Necessary and sufficient conditions for minimum has been worked out using the adjoint problem. When a linearization of the Navier Stokes equations was used in the above analysis, the task of computing the feed back map reduces to that of finding the solution of a Riccati type partial differential equations. (These results will be presented in the SIAM meeting at San Diego in July, 1989.)

Plans for Next Year's Research

Stimulated by the breakthrough made in the optimal control of hydrodynamics the past year, we have decided to focus on two control problems. The first one is the task of finding the optimal way to accelerate an obstacle from rest to a given speed in a given time. The reverse of this problem is also important as it models the aerobraking maneuver. The second problem deals with the task of finding optimal velocity distributions (suction and blowing) on an obstacle to minimize the drag. A mathematically related problem is shape optimization in viscous flow. The cost functional for each of these problems can be easily written down and is quadratic in nature.

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

   "Analysis of Regularized Navier Stokes Equations - I," submitted to *Pacific Journal of Mathematics*, March 1988, joint author Y. R. Ou.

   "Invariant Manifold Theory for Hydrodynamic Transition," submitted to *Acta Mathematica*, July 1988.

   Analysis of Regularized Navier Stokes Equations - II," submitted to *Pacific Journal of Mathematics*, Y. R. Ou, February, 1989.

2. Technical Reports

   "Analysis of Regularized Navier Stokes Equations - II," ICASE report 89-14, joint author Y. R. Ou.

   "Invariant Manifold Theorems for the Navier Stokes Equations," Proceedings of the Oberwolfach workshop on *Theory and Numerical Methods for Navier Stokes Equations*, to appear on *Springer Lecture Notes.*

3. Presentations (invited seminars)

   "Invariant Manifold Theorems for the Navier Stokes Equations" SIAM Annual meeting, July 1988, Minnesota.

   "Invariant Manifold Theorems for Conventional and Regularized Navier Stokes Equations" Invited Seminar, Mathematisches Forschunginstitut Oberwolfach, West Germany, September, 18-24, 1988

"On the Existence Theory of Viscous Time Dependent Flow Past Noncompact Boundaries," Invited Seminar in Mathematical Sciences Department, San Diego State University, February, 23, 1989.

List of Honors/Awards

None

List of Participants

S. S. Sritharan, Assistant Professor

Y. R. Ou, Graduate Student, presently staff scientist ICASE (not supported by URI contract).

J. G. Heywood, Professor, University of British Columbia, consultant.

AIAA'88

AIAA-88-0134
The Effects of Longitudinal Roughness Elements upon the Turbulent Boundary Layer

R. F. Blackwelder and J. B. Roon,
University of Southern California, Los Angeles, CA

Abstract

Velocity profiles and bursting statistics were measured in the presence of cylindrical longitudinal roughness elements (LREs) and compared to similar work by Johansen and Smith.[1] An algorithm was devised to detect low speed streaks (LSS) from the hot-wire rake data, allowing an estimation of the LREs ability to reduce spatial randomeness of the sublayer structure. The velocity profiles agree with Johansen and Smith's result that the effects of the LREs are felt only for $y^+ \leq 15$. The analysis of the bursting statistics and LSS algorithm output shows that the flow relaxes back to a flat plate boundary layer between the LREs. A crude first approximation is that the LREs simply impose the no-slip boundary condition at an elevation equivalent to their diameter. While the LREs might serve as a nucleation site for the LSS, spatial randomness of the structure is effected only very close to the LREs.

AIAA 26th Aerospace Sciences Meeting

January 11-14, 1988/Reno, Nevada

AIAA'89

AIAA-89-1009

Some Ideas on the Control of Near-Wall Eddies

Ron F. Blackwelder
University of Southern California
Los Angeles, California 90089-1191

Abstract

The near-wall region of bounded turbulent flows *consists of streamwise vortices, low speed streaks, intense shear* layers, inflectional velocity profiles, oscillations and ejections of low speed fluid out into the logarithmic layer. A mass of data has accumulated over the past 25 years concerning this important chain of events, however the general picture is still rather suggestive rather than conclusive. Some proposals are offered as means of interacting with and/or interrupting the sequence of these events in the wall region.

AIAA 2nd Shear Flow Conference

March 13-16, 1989 / Tempe, AZ

The American Society of
Mechanical Engineers

Reprinted From
Nonlinear Interaction Effects and Chaotic Motions – Volume 7
Editors: M. M. Reischman, M. P. Paidoussis, R. J. Hansen
(Book No. G00447)

A TECHNIQUE FOR ACOUSTIC EXCITATION OF SEPARATED SHEAR FLOWS: PRELIMINARY RESULTS

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Department of Aerospace Engineering
University of Southern California
Los Angeles, California

ABSTRACT

The turbulent region contained between two parallel streams of unequal speed is the prototypic separated flow. The application of small acoustic perturbations (or excitations by a trailing edge flap) can cause the flow to grow more rapidly or less rapidly depending upon the forcing frequency. The effect of forcing is either to promote or discourage interactions among the large, nearly spanwise vortices. Here we study a means for producing complex acoustic forcing. The forcing is applied with a linear arrangement of small speakers placed across the span of the flow in the wind tunnel ceiling. Flow response is observed with a rake of hot wires placed across the span of the flow at selected downstream positions.

1. INTRODUCTION

It is well established that unbounded turbulent shear flows are particularly sensitive to the application of a small, external disturbance. This conclusion is supported by a variety of experiments performed over the past 15-20 years (c.f. Ho and Huerre [1], Browand and Ho [2]), and by a lesser but increasing number of numerical (computational) experiments. Ho and Huerre contains an extensive bibliography. The physical mechanism responsible for this controlling influence is partially understood as follows. Shear flows which are free from boundaries, such as jets, wakes, and mixing layers, usually arise as a result of flow separation. When laminar, these flows are extremely unstable, and boundary layer vorticity is collected into discrete clumps, forming the largest scale features of the developing turbulent flow. When the boundary layer at separation is turbulent, a similar process seems operative, and the result is again rapid formation of lumps of vorticity. These vortical regions are—to first approximation—simply rearrangements of the preexisting boundary layer vorticity. Thus in flows which are approximately two-dimensional, the vortices are oriented with vorticity perpendicular to the plane of motion, while for axisymmetric flows, the vortices are rings or donuts lying in planes perpendicular to the axis of symmetry.

The downstream growth of the turbulent region is the result of interactions between neighboring vortices--often involving mergings to form larger structures with greater spacings. The application of a small, spatially coherent perturbation--for example, by use of an oscillating flap at the plate trailing edge or jet nozzle--creates a stronger, more coherent vortex structure. In the subsequent downstream development, these vortices undergo interactions and rearrangements which can be quite different

To appear in the proceedings of "New Trends in Nonlinear Dynamics and Patterning Phenomena: The Geometry of Non Equilibrium". NATO ASI Series B, P. Coullet & P. Huerre, editors, New York/London: Plenum.

Experiment on Pattern Evolution in the 2-D Mixing Layer

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INTRODUCTORY REMARKS

The first detailed, quantitative study of the 2-D mixing layer was completed by Liepmann and Laufer in 1947. They described this technologically important flow in terms of the variation of the mean velocity and various mean fluctuation intensities. The measurements were of high quality, and have scarcely been improved upon in the intervening forty years. Yet they give very little fundamental understanding of the structure of the flow. What has changed within the past twenty years is the increased concern with *process* in turbulent flows. Today turbulent flows are perceived to contain identifiable structure. The *interaction of structure* is the turbulent *process*. Thus *process* attempts to provide a dynamical description of the flow, and is a more ambitious undertaking than a simple description of the *state* of the flow.

The identification of structure in highly turbulent flows first came about by relatively simple visualizations using dye or hydrogen bubbles. These techniques allowed the viewing of selected volumes or areas within the flow in a manner not possible with single point velocity measurements. Spatial patterns and pattern evolution are emphasized in these qualitative visualizations. We are now beginning to ask quantitative questions about pattern evolution. This has only become possible within the past ten years or so, as the result of inexpensive computers having vastly increased storage capacity.

The present experiment is an attempt to describe a high Reynolds number, highly turbulent shear flow from a geometrical point of view, and is an outgrowth of earlier work by Browand and Troutt, (1980, 1985). Here we extend these concepts to include an evolution equation model as has been shown to be effective in the study of the Rayleigh-Benard and Taylor-Couette flows. The companion analytical/numerical effort by Yang, Huerre, and Coullet is presented in the paper immediately following. The long-term goal is to provide a combined mathematical-experimental model which will quantitatively describe the evolution of the large scale structure in the highly turbulent regions of the flow. To date, we concentrate on describing the initial instability region where a small range of scales is present. The comparisons with theory are largely qualitative at this stage.

DESCRIPTION OF THE EXPERIMENTAL APPARATUS

The experiment is performed in a large wind tunnel. A side view of the test section is shown schematically in figure 1. The mixing layer is produced by the merging of two parallel streams at the termination of a splitter plate. Flow speeds are on the order of 5-20 m/sec. The inital thickness of the laminar shear layer, δ_i, is about 2.3 mm. The width of the wind tunnel — expressed in multiples of this thickness — is about 400. The Reynolds number, based upon

Heat Transfer Enhancement
in
Rayleigh-Benard Convection

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Direct numerical simulations of 3-D Rayleigh-Benard convection were performed with non-uniform temperature boundary conditions at the lower plate. The boundary conditions excite convective states in a form of counterrotating convective rolls that remain stable for at least ten eddy-turnover times even if their size is significantly different from the size of rolls encountered in the natural convection at the same Rayleigh number. For longer times applied temperature forcing becomes ineffective and forced convective patterns lose their stability. Changing the size of the convective elements increases heat transfer by about 15-20% as compared with case of the natural convection.

Accepted for publication in <u>Int. J. Heat & Mass Transfer</u>.

Local Energy Transfer and Nonlocal Interactions in Homogeneous, Isotropic Turbulence

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April,1989

Abstract

Detailed measurements were made of energy transfer among the scales of motion in incompressible turbulent fields at low Reynolds numbers generated by direct numerical simulations.It was observed that although the transfer resulted from triad interactions that were nonlocal in k space, the energy always transferred locally. The energy transfer calculated from the EDQNM theory of turbulence at low Reynolds numbers is in excellent agreement with the results of the numerical simulations. At high Reynolds numbers the EDQNM theory predicts in the inertial range the same transfer mechanism which is observed at low Reynolds numbers i.e. predominantly local transfer caused by nonlocal triads.The weaker, nonlocal energy transfer is from large to small scales at high Reynolds numbers and from small to large scales at low Reynolds numbers.

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Nuclear Physics B (Proc. Suppl.) 2 (1987) 159-178
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EVOLUTION OF COHERENT STRUCTURES IN SHEAR FLOWS: A PHASE DYNAMICS APPROACH

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A general amplitude evolution model is proposed to describe the development of instability waves in parallel free shear flows which are invariant under both space translations and Galilean transformations. It is argued that temporal and spatial modulations of finite-amplitude states are strongly coupled with a marginally unstable large-scale horizontal velocity field. As a result, an array of spatially periodic coherent structures is shown to exhibit two distinct types of phase instabilities: an Eckhaus-like modulational instability dominated by two-dimensional disturbances and a fully three-dimensional secondary instability generated by coupling between pattern deformation and advection by the large scale field. Anisotropic phase waves can also travel on the basic array, the global velocity field acting as a restoring force. Applications of these concepts to the phase dynamics of Kelvin-Helmholtz vortices are briefly considered.

1. INTRODUCTION

The evolution of free shear flows such as mixing layers, two-dimensional jets and wakes is dominated, at high Reynolds numbers, by large scale vortical structures which develop as a result of the instability of the basic velocity profile. In particular, recent experimental evidence[1-4] has indicated that the instability of free shear layers leads to the formalism of quasi-two dimensional spatial patterns exhibiting localized dislocations in the spanwise direction. Some of the experimental results obtained by Browand are illustrated in Figure 1. The goal of the present work is to outline a phase dynamical description of the long-range evolution of such features over many characteristic length scales and time scales of the flow. The phase dynamics formalism has been used with great success in the past to study the slow variations of similar spatial patterns arising in weakly nonlinear conservative waves[5], chemical reactions[6-8], Rayleigh-Bénard convection[9-11], and Taylor-Couette flow[12]. It is felt that a similar approach could be fruitful in describing the slow meanderings of Kelvin-Helmholtz vortices as observed in Figure 1.

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(North-Holland Physics Publishing Division)

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A TWO DIMENSIONAL MODEL OF PATTERN EVOLUTION IN MIXING LAYERS

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1 INTRODUCTION

The evolution of coherent structures in shear layers and wakes provides a particularly simple example of pattern dynamics in open spatially-developing non-equilibrium systems. As in closed flows such as Rayleigh-Bénard convection, one observes a wealth of possible flow configurations involving dislocations, periodic arrays of vortices with distinct orientation, quasi-two dimensional vortical arrangements, etc. However, in contrast with Rayleigh-Bénard convection, the presence of a basic shear lifts the orientational degeneracy: vortices tend to remain more or less perpendicular to the flow direction.

The geometry of three-dimensional patterns in mixing layers has been extensively studied from an experimental point of view by Browand and his colleagues [see for instance Browand (1986), Browand & Ho (1987) and in this volume, Browand & Prost-Domasky (1989)]. These experiments have clearly and carefully documented the generation of defects in nearly periodic arrangements of spanwise vortices. Recent experiments by Stuber & Gharib (1988) have demonstrated that complex spatio-temporal regimes result from external forcing of dislocations in wakes. Lateral boundaries can also considerably affect the direction of shedding and lead to oblique patterns as shown by Williamson (1989). The present investigation should be viewed as an attempt at a theoretical description of some of these phenomena in the specific context of Browand

Invariant manifold theory for hydrodynamic transition

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Abstract

The hyperbolicity property of the time periodic solutions to the Navier Stokes equations is studied.Existence,uniqueness and analyticity of the invariant manifolds are established.

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Invariant manifold theorems for the Navier Stokes equations

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We will present certain results on the structure of attractors for the Navier Stokes equations. Ladyzhenskaya [4] proved that the time dependent viscous flow in two dimensional bounded domains can be characterized by a compact global attractor. This attractor contains in particular the steady, periodic, quasi-periodic and almost periodic solutions. Such a result for three dimensional flow would be of great interest in the theory of turbulence. Another open problem is the task of proving the existence of global finite dimensional invariant manifolds containing the attractor. Coordinates of such manifolds would provide us with an effective means of computing the properties of the attractor (which may be of fractional dimension.). In this report we will present certain preliminary results towards this subject. Let us first describe our results [8] on the hyperbolicity of periodic solutions of the Navier Stokes equations in bounded domains. Analyticity of the invariant manifolds is the central result. For earlier studies on hyperbolicity see [5],[2].

Let $\Omega \subset \boldsymbol{R}^n, n = 2$ or 3 be a smooth bounded domain. We will consider the problem of finding $(\boldsymbol{u}, p) : \Omega \times (0, \infty) \rightarrow R^n \times R$ such that,

$$\boldsymbol{u}_t + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla p + \Delta \boldsymbol{u} \qquad \text{in } \Omega \times (0, \infty)$$

Analysis of Regularized Navier-Stokes Equations[1]

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Abstract

A practically important form of regularization of the Navier-Stokes equations is analyzed. Global existence and uniqueness is established for two classes of generalized solutions. It is shown that the solution of this regularized system converges to the solution of the conventional Navier-Stokes equations for low Reynolds numbers. Other results obtained are the existence theory of periodic solution and the squeezing property of solutions.

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ANALYSIS OF REGULARIZED NAVIER-STOKES EQUATIONS -II

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ABSTRACT

A practically important regularization of the Navier-Stokes equations have been analyzed. As a continuation of the previous work, we study in this paper the structure of the attractors characterizing the solutions. Local as well as global invariant manifolds have been found. Regularity properties of these manifolds are analyzed.

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NASA Contractor Report 181801

ICASE REPORT NO. 89-14

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THE THEORY OF NONSTATIONARY VISCOUS FLOW PAST PLANE DOMAINS WITH NONCOMPACT BOUNDARIES

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ABSTRACT

In this paper we establish the existence and uniqueness of generalized solutions for time dependent viscous flow past plane domains which have outlets which may or may not expand at infinity. These solutions carry the prescribed time dependent flux through the outlets.

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Nonlinear Stability of Subsonic Mixing Layers With Symmetric Temperature Variations

by

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ABSTRACT

The nonlinear evolution of stability waves in mixing layers of a perfect gas with a symmetric mean temperature profile is studied for subsonic Mach numbers in the high Reynolds number limit where viscous and thermal diffusion effects enter first and dominate in the critical layer. The linear, neutral eigensolution of the inviscid theory for temperature profiles having either an excess or deficit of mean temperature in the shear layer is used as a basis for the weakly nonlinear, slightly viscous analysis. The coefficients of viscosity and thermal conductivity are assumed to have a power law dependence on the temperature and the effect of viscous dissipation is included. An analytical expression for the Landau constant, and other constants appearing in the nonlinear evolution equation for the amplitude of the eigenmode, have been obtained. It is found that the temperature excess/deficit at the critical level and the Mach number have a strong nonlinear effect, even to the extent of changing the sign of the Landau constant.

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AIAA'89

AIAA-89-1020
STABILITY PROPERTIES OF SUBSONIC MIXING LAYERS

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Abstract

Linear and nonlinear stability properties of subsonic mixing layers with variable mean temperature profiles are discussed. Spatial stability characteristics are presented as a function of the Mach number and the velocity ratio for mixing layers with two different families of temperature profiles . The critical velocity ratio for which the absolute-convective character of the instability changes at various Mach numbers and temperature ratios is also computed. An analysis of the nonlinear, self-interaction of marginal disturbances in two mixing layers is also summarised. The two mixing layers differ in the symmetry properties of the mean flow profiles. It is found that the Mach number and temperature ratio, together with the profile symmetry, can significantly change the nature of the bifurcation from the marginal state. The nature of the bifurcation can change from supercritical to subcritical at high subsonic Mach numbers and the type ofthe bifurcation changes from stationary to Hopf as the profile symmetry is broken.

AIAA 2nd Shear Flow Conference

March 13–16, 1989 / Tempe, AZ

Abstract for 22nd Combustion Symposium Poster Presentation

VORTEX DYNAMICS IN AN ISOTHERMAL RECTANGULAR DUMP COMBUSTOR*

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Due to the enhanced mixing properties of small aspect ratio elliptic jets interest has developed recently in asymmetric combustion chambers for ramjets. Little is currently known about mixing and shear layer reattachment in confined asymmetric jets. Therefore, an experimental study of isothermal flow in a rectangular duct which undergoes a sudden expansion is being conducted in order to understand the basic dynamics of this type of configuration. The long range goal of this study is to be able to control reattachment and mixing and thus, combustion efficiency, through active or passive means.

The first phase of the work involves flow visualization of the roll up vortices in the free shear layer and the structure of the region where the shear layer reattaches to the walls. To this end a rectangular ducted dump water channel has been constructed of plexiglas. Two jets are being investigated: a 3.8 cm square and a 3.8 x 7.6 cm rectangular crossection. The dump section can be varied from a single sided backward facing step to a full centered rectangular 6:1 area increase. The jet Reynolds number can range from 2000 to 10,000.

Preliminary results have been obtained for an impulsively started rectangular jet with a 6:1 area increase, Re = 2000. Using hydrogen bubble flow visualization the free shear layer at the jet exit has been observed to roll up into rectangular vortices which quickly become distorted due to the self induction effect of asymmetric vortex rings. Since the radius of curvature of the ring is smallest in the corners, these regions are convected ahead of the rest of the ring until the ensuing distortion increases the curvature in the rest of the ring, which catches up. The same effect causes the ring as a whole to switch major and minor axes. By the time this occurrs the ring has spread so that the ends of the new major axis are now close to the wall, which causes the section of vortex ring there to stretch and intensify. At this point the effects of confinement dominate the dynamics of the vortex corners as the corner sections of the ring are bent through 180 degrees by the perpendicular sidewalls, resulting in an apparent reversal of vorticity.

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THE FOURTH ASIAN CONGRESS OF FLUID MECHANICS
August 19-23, 1989 Hong Kong

ENTRAINMENT OF 3-D SHEAR LAYERS

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ABSTRACT In engineering devices involving chemical reaction, it is important to be able to control the mass transfer between two streams of fluids. Ho and Gutmark [1] used a small aspect ratio elliptic jet which can significantly enhance the entrainment. This efficient passive control technique is due to the unsteady deformation of 3-D vortical structures caused by self-induction.

1.Passive and Active Control of Free Shear Layers

The possibility of controlling the mass transfer in the transverse direction of a shear layer is important in improving the efficiency of devices with chemical reaction. In a two-dimensional flow, the coalescense of the vortical structures in the shear layer was identified to be the main entrainment mechanism [2]. If the vortex merging is prohibited, the growth of the mixing layer is stopped or even decreased [3]. On the other hand, if the shear layer is actively perturbed by the subharmonics of the most amplified frequency, multiple vortices will merge simultaneously [4]. The growth of the shear layer is increased.

The spatial development of the shear layer is extremely sensitive to the initial perturbations or the boundary conditions. The alternative approach of controlling the enhancement is to change the upstream boundary condition of the shear layer. Ho and Gutmark [1, 5] found that a jet with an elliptic nozzle can entrain much more fluid than that of a circular or a plane jet [Fig. 1]. This passive control method is even more advantageous for engineering applications, because no delicate forcing arrangement is required. More importantly, they identified a new entrainment mechanism; the self-induction of an elliptic vortex ring makes the structure switch its axis orientation, the vortex element near the minor axis moves outward and makes a large amount of ambient fluid move into the jet near the minor axis region. This concept can be generalized and used in other flow configurations, such as combustion chamber.

2.Applications in Combustion

The ramjet is a device which can be benifited by the entrianment contol technique. There is a short distance from the flame holder to the exhaust nozzle. Combustion needs to be accomplished during a short residence time and combustion

instability has been a troublesome problem. The advantages of using an elliptic jet in the ramjet has been shown to be phenomenal. Schadow et al. [6] used a 3:1 elliptical nozzle in a jet with combustion. They found that the centerline temperature increased sharply a short distance from the elliptic nozzle. At the end of the jet potential core, the temperature
was much higher than that of a circular jet [Fig. 2].

The combustion instability problem was alivated by using another type of asymmetric nozzle. They used a triangular nozzle and injected fuel near the tips of the triangle [7]. In this way, the fuel is mixed by the small eddies near the tips and the large structures do not trigger the combustion instability.

3.Supersonic Asymmetric Jet

The spreading rate of a supersonic shear layer is much slower than that of a subsonic flow and the combustion efficiency of supersonic flame is hindered by the low mixing rate. Actually, this is the most pressing problem in developing a hypersonic aircraft. In a preliminary experiment, we found that the small aspect ratio rectangular nozzle could enhance the entrainment as it did in the subsonic flow [8].

In general, the supersonic flows spread slower than that of subsonic flows. However, the entrainment improvement of the rectangular nozzle over the circular nozzle is about the same for both supersonic and subsonic jets in the far downstream locations. Near the Nozzle, the variations of the cross-section area ratios, indicating the shear layer spreading, are similar for supersonic and subsonic cases. Hence, we expect that the supersonic rectangular jet will entrain more mass than that of a supersonic circular jet in the region near the nozzle.

4.Asymmetric Jet in Confinement

Most of the combustion is taking place inside a confined space. The entrainment process is very different from a shear layer in the free space. As has been pointed out in our previous findings [1] the <u>unsteady</u> evolution of the vortex structures can engulf the fluids into the mixing region. We used a 2:1 aspect ratio rectangular jet in a confined environment. The deformation of the vortical structures was found to be much more convoluted than those in a free jet. These deformations are produced by the local 3-D shear layer and the induction of the image vortex. In other words, a properly designed confinement should be able to facilitate the mixing process.

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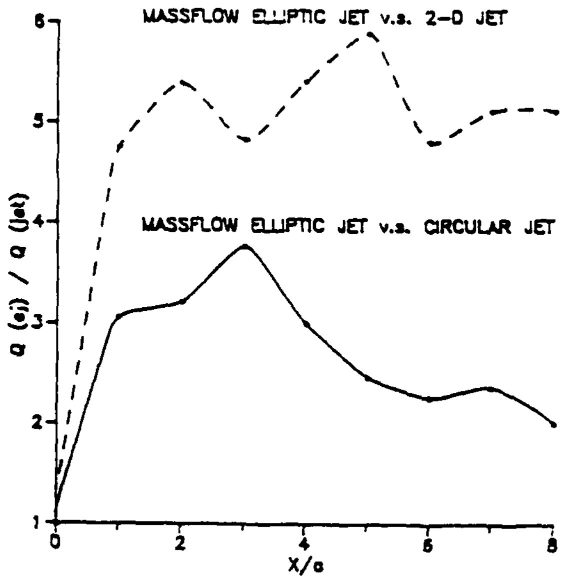

Fig. 1 Mass entrainment rate

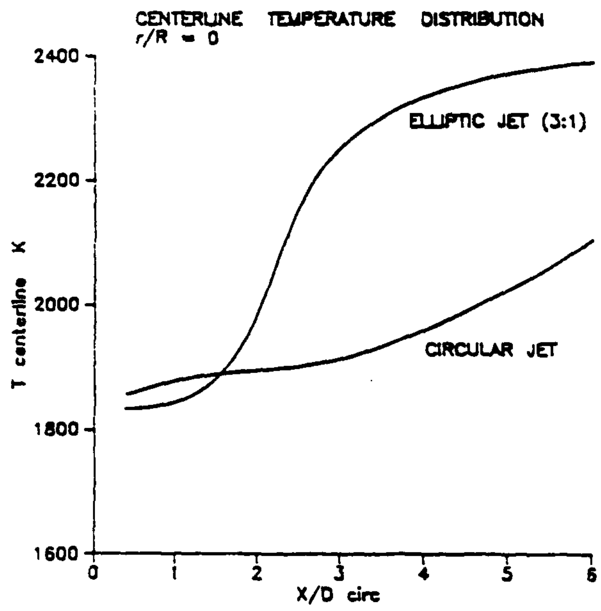

Fig. 2 Centerline temperature

Abstract of a paper presented at the International Congress of Theoretical and Applied Mechanics, Grenoble, France, August 22-28, 1988.

Vortex Patterns in High Reynolds Number Shear Flow

by F. K. Browand and S. Prost-Domasky

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The turbulent region contained between two parallel streams of unequal speed is the prototypal separated flow. Such a mixing layer occurs in external flows separating from wing or body surfaces, and in many internal flows having backward facing steps or co-flowing streams. In the laboratory, this flow is created by merging two low turbulence streams at the termination of a splitter plate. The laminar boundary layers from the splitter plate form the region of high shear; in the lateral (spanwise direction), the flow is sensibly uniform.

As a result of the initial instability, the vorticity in the shear layer is gathered into vortex tubes which are aligned along the span. Ideally, these vortices are perfectly oriented to produce a two-dimensional flow (the lateral walls are far removed and do not influence the flow). But small, unavoidable irregularities in the flow do break symmetry in the lateral direction, and the naturally evolving flow contains both skew vortices and other more singular defects which do not conserve phase fronts locally. A quantitative measure of defect density is found to increase in the downstream direction until an asymptotic value is reached.

The development and maintenance of this two-dimensional vortex structure can be conveniently studied by application of a variety of space/time acoustic forcings utilizing a linear arrangement of small speakers located in the wind tunnel ceiling. This phased array is driven by computer generated pulse trains. Flow response is observed with a rake of hot wires placed across the span of the flow at selected downstream positions. Plotting velocity as a function of span and time gives a useful visualization of the large scale vortex structure. The formation and subsequent evolution of defects will be discussed.

Abstract Submittal Form for the 41st Annual Meeting of the Division of Fluid Dyanmics of the American Physical Society

Vortex Patterns in High Reynolds Number Shear Flow* BROWAND, F.K. & PROST-DOMASKY, S., Univ. So. Calif.--Turbulent structure in the developing mixing layer is studied in terms of the geometry of the vortices which make up the largest scale features. Defects in vortex structure can be quantified by making simultaneous velocity measurements at many points along the span (the translationally invariant direction). Vortex patterns are never defect free, and the number of defects is shown to increase in the downstream direction until an asymptotic value is reached. Acoustic forcing is applied utilizing a linear arrangement of small speakers located in the wind tunnel ceiling. This phased array is driven by computer-generated pulse trains, and allows the evolution of defects to be studied in detail.

*This work was supported by the ONR/URI Contract No. N00014-86-K-0679.

Abstract Submittal Form for the 41st Annual Meeting of the Division of Fluid Dyanmics of the American Physical Society

On the Convective Nature of the Görtler Instability*, PARK, D. & HUERRE, P., Univ. So. Calif.--The Görtler instability arising in the boundary layer on a concave plate is studied from the point of view of its convective/absolute nature. To avoid difficulties due to the nonseparable character of the problem, the boundary layer velocity field is chosen to be the asymptotic suction velocity profile of constant momentum thickness along the stream. This basic flow field is characterized by a unique neutral curve for the Görtler instability and the complex dispersion relation is obtained numerically for arbitrary wavenumbers k_x and k_z along the streamwise and spanwise directions respectively. Direct calculations indicate that the impulse response (or Green's function) takes the form of a wavepacket propagating downstream. The packet remains localized in the streamwise direction but its "wing tips" diffuse rapidly in the spanwise direction. One can conclude that the Görtler instability is convective: Görtler vortices observed in practice are likely to be very sensitive to upstream perturbations: they are the result of the amplification of external fluctuations.

*Supported by ONR under ONR/URI N00014-86-K-0679.

Models of Pattern Formation and Dislocations in Free Shear Flow*, YANG, R. & HUERRE, P., Univ. So. Calif. & COULLET, P., Observatoire de Nice.--The three-dimensional evolution of Kelvin-Helmholtz vortices in free shear flows is modelled a-la Swift-Hohenberg by a two-dimensional equation for the amplitude of the vortices. As a result of Galilean invariance, deformations of the structures are coupled to a large scale vertical vorticity field. Numerical and analytical studies of the model indicate that collective oscillatory motions may arise when an initially two-dimensional array of vortices is perturbed in the skew-varicose mode of instability. In such collective oscillations, the restoring force is provided by the vertical vorticity field. Spatial inhomogeneities in the local wavenumber can also induce pattern dislocations which are qualitatively similar to those observed in free shear layers by F.K. Browand. Lines of constant phase meet at the center of a defect and the amplitude of the perturbations decays to zero. Interactions between several of these phase singularities are studied numerically.

*Supported by the U.S. Office of Naval Research under ONR/URI Contract No. N00014-86-K-0679.

Abstract for Nov. 1987
A.P.S. Meeting Presentation

Modification of Turbulent Boundary Layers by Longitudinal Roughness Elements.* JASON B.ROON, RON F. BLACKWELDER, Univ. So. Calif. and MOHAMED GAD-EL-HAK, Univ. Notre Dame— Velocity profiles and bursting statistics were measured in the presence of Longitudinal Roughness Elements (LRE's) and compared to similar work by Johansen and Smith (1986). An algorithm was devised to count low speed streaks (LSS) and measure their length from the hot-wire rake data, enabling determination of the LRE's ability to minimize the LSS's spatial randomness. The velocity and turbulence intensity profiles agree with Johansen and Smith's result that the effect of the LRE's are felt only out to $y+ \approx 10$. However the analysis of the bursting statistics and LSS algorithm output suggest that while the LRE's might serve as a nucleation site for LSS formation, their ability to lock the fully formed LSS's onto the LRE's is minimal and hence spatial randomness was not eliminated.
*Supported by NASA under Contract NAS1-18292 and ONR-URIP N00014-86-K-0679.

Abstract for Nov. 1988 A.P.S. meeting presentation

VORTEX DYNAMICS IN A RECTANGULAR SUDDEN EXPANSION* J. Hertzberg and C.M. Ho, University of So. Cal.-- An experimental study of a 2:1 aspect ratio rectangular jet which undergoes a 6:1 sudden expansion is being conducted in order to understand entrainment and mixing in this type of configuration. Preliminary results have been obtained for impulsively started flow using hydrogen bubble flow visualization. The effect of self induction and confinement on the rectangular starting vortex ring greatly enhance the unsteady distortion of the ring. Hence, large entrainment ratios are expected. Further hydrogen bubble visualization in continuous flow have revealed quasi-instantaneous velocity profiles in the recirculation and reattachment regions. Laser doppler anemometry studies are also in progress to provide quantitative information on the flow structure.

***This work is supported by an O.N.R.- U.R.I.**

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Regularity of Inertial Manifolds for Semilinear Evolution Equations

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It has been realized recently by several authors that the solutions of certain class of evolution equations can be characterized by exponentially attracting Lipschitz global manifolds. These manifolds contain the global attractor. Coordinatization of these manifolds will provide us with an exact Galerkin method for the solution of the evolution system. These manifolds are modelled on the spans of the eigenspaces of certain self adjoint operator. In this talk we will discuss the regularity properties of these manifolds. We will show in particular that the higher dimensional manifolds are automatically C^1.

Theory of Nonstationary Viscous Flow Past Plane Domains With Noncompact Boundaries

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Existence theory of nonstationary viscous flow past plane domains has been an open problem for the past decade. In this talk we present the existence and uniqueness of generalized solutions for time dependent flow past domains which have outlets which may or may not expand at infinity. These solutions carry the prescribed time dependent flux through the outlets. The corresponding three dimensional problem is relatively simpler and has already been resolved due to the works of Heywood and of Ladyzhenskaya and Solonnikov a few years ago.

Optimal Control Theory of Navier Stokes Equations

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In this talk we will present certain results on an application of distributed systems theory to a hydrodynamic problem. Existence of optimal solution that minimizes a given cost functional is established. As a special case we then consider the linearized Navier Stokes equation. In this case the original system, the adjoint system and the feedback equation are combined to give the Riccati partial differential equation for the computation of the feedback map.

"Navier Stokes Equations"
Mathematisches Forschunstitut OBERWOLFACH
Sept. 18-24, 1988

S. SRITHARAN:

Invariant manifold theorems for the Navier-Stokes equations

Invariant manifold theory lays a bridge between the onset dynamics of turbulence and the theory of finite dimensional dynamical systems. In this talk we will describe the existence,uniqueness and analyticity of local invariant manifolds along with the characterization of the non-linear hydrodynamic semigroup and the monodromy operator. These manifolds are constructed in the neighborhood of each periodic solution to the Navier Stokes equations establishing the hyperbolicity of these solutions. For a particular regularization of the Navier Stokes equations (for which we have global existence and uniqueness theorem) we are able to prove the existence of global invariant (also known as the inertial) manifolds. This result is significant since the (generalized) solution of the regularized system has a strong limit (as the regularization parameter approaches zero) to the weak solution of the Navier Stokes equations.

SIAM Annual Meeting
July 11-15, 1988
University of Minnesota

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Invariant Manifold Theorems For the Navier Stokes Equations

We have established the hyperbolicity of stationary and time periodic solutions of the Navier Stokes equations with analytic stable and unstable manifolds. Moreover, the spectral properties of the monodromy operator (the frechet derivative of the nonlinear semigroup) have also been studied. For a regularized version of the Navier Stokes equations, both local and global invariant manifold theorems have been established.

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