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13. ABSTRACT (Maximum 200 words)
Research was conducted which exploited the use of modern theoretical methods in nonlinear dynamical systems, fluid dynamics, and nonlinear distributed parameter control, to understand and control the dynamics of the turbulence process in turbulent boundary layer flows.

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Technical Report

Contributions

to

F49620-92-J-0287 (Wall Layers)

and

Current Research Directions

1 October 1994- 30 September 1995

Dr. Marc Q. Jacobs, Program Manager

Principal Investigators

John Guckenheimer
Philip Holmes
Sidney Leibovich
John L. Lumley

N.B. - This contract expired May 30, 1995, and received a no-cost extension to November 30, 1995. All funds are now expended. Note that John Guckenheimer is on Sabbatical Leave.

2. Objectives.

To explore the possibility of control of the turbulent boundary layer by the use of low-dimensional models developed using dynamical systems theory; to investigate mathematical and physical questions arising in this connection.

3. Abstract of progress.

We have completed a direct numerical simulation of turbulent channel flow with a movable bump on the wall. We have studied the dynamical effect of such a bump. Using this code, we have investigated turbulence control using the bump in various ways. Although these attempts are largely ad-hoc, we have been able to achieve significant reductions in drag.

We have investigated the effect of one type of control on our low-dimensional models, and have demonstrated reductions in bursting frequency comparable with the drag reductions observed with polymer additives, as we expected on theoretical grounds. We have also demonstrated drag reduction on the Kuramoto-Sivashinsky equation using a type of control equivalent to boundary deformation.

We have explored the problem of sensing the state of the flow from arrays of sensors at the surface. We have found that it is possible to determine the state of the flow with a correlation in the neighborhood of 0.6 or better from surface information.

We have successfully generated streamwise vortex pairs in a DNS of turbulent channel flow, and are examining the interaction between these vortex pairs and naturally occuring coherent structures.

We have explored the possibility of using wavelet decompositions to replace Fourier decompositions in our low-dimensional models. We have found that there are serious unforseen difficulties in doing so, despite the otherwise attractive features.

LES of nonequilibrium turbulence with strong periodic forcing has been formulated and implemented. This is expected to be relevant to the periodic forcing experienced in turbine and compressor blade passages.

We are now embarking on a numerical evaluation of several of the assumptions which we made in constructing our coherent-structure models, the periodicity assumption among others.

4. Summary of accomplishments.

Our DNS of turbulent channel flow with a temporally deformable wall has been quite successful. This is the first DNS of flow over a wall deforming in real time. We have found that our expectations for the flow induced by a bump were not realistic. We found that the boundary layer vorticity overturned by the bump is not an important player in the flow induced by the bump. Rather, the vorticity generated at the surface by the flow's being turned aside by the bump, and turning in behind the bump to reform, is a much more important player. As the flow splits, it generates a vortex pair, and when it recombines it generates another. Since the upstream pair is convected downstream, this produces stacked opposite vortex pairs - the upstream pair has a updraft in the middle, while the downstream pair which forms under it has a downdraft in the middle. The necklace vortex, which is relatively weak, has a downdraft in the middle, and lies on top of the other two pairs downstream of the bump. This complex pattern has an effect on the naturally occurring vortices, but not the anticipated one, nor is it particularly efficient in controlling the flow, since the vortex pairs are mutually canceling, and produce little effect at some distance.

We now feel that a more efficient actuator would be something like the flaps described by Ho Chih Minh, which have sharp edges, and should generate more nearly simple vortex pairs. Unfortunately, these cannot be computed exactly with our program, since the mesh cannot resolve the sharp edges that are essential to generate the vortices. Fortunately, such vortices can be generated by body forces, and we have successfully done so.

The complex vortex pattern produced by the bump can produce drag reduction by the simple mechanism of lifting the high speed streak away from the surface. We have found that the effect disappears when the velocity field generated by the bump is convected out the downstream boundary of the flow region, and back in at the upstream boundary (due to the periodic boundary conditions). When it reaches the bump again, the drag suddenly rises. We have experimented with a fringe which damps any disturbance which leaves the region and comes in the upstream boundary. Unfortunately, this also damps the turbulence, which depends on the turbulent field coming in the upstream boundary to maintain itself.

Most of our models make use of Fourier transforms in homogeneous directions. This is workable but unrealistic, in that the flow structure in these directions is usually not periodic. A wavelet decomposition would be more useful, since it is composed of isolated disturbances. Such decompositions have been successfully applied to fully homogeneous flows. We have found that the combination of incompressibility and partial homogeneity which is so convenient to deal with in the Fourier representation presents apparently insuperable difficulties in a wavelet representation.

Large eddy simulation of turbulent flows forced by strong time-periodic disturbances have been carried out in the context of Langmuir circulation (S. Leibovich and G. Yang). The methods of treating the non-equilibrium forcing is novel and should be applicable to flows, such as those found in turbine blade passages, that also are affected by stong periodic forcing.

N. Aubry's research team (two post-docs and two students have joined her at Cornell, where she is spending her sabbatical) has been investigating fully developed turbulence and transition to turbulence (including nonlinear waves), using a spatio-temporal, unified, approach. The specific flows she and coworkers have been looking at include turbulent boundary layer and channel flow, turbulent and transitional wake flows, (free-surface) spilling breaking waves, binary fluid convection and transitional film flows. Recently, they have been interested in the dynamics of outward propagating flames as well. Aubry's team will continue to work alonmg these lines during the coming year. It is clear that there are many points of contact between their work and ours, and we exect a year of productive collaboration.

5. List of Personnel:

Faculty: J. L. Lumley (Cornell, PI); S. Leibovich (Cornell); J. Guckenheimer (Cornell); G.Berkooz (Cornell/BEAM Technologies); Dietmar Rempfer (Stuttgart); N. Aubry (CUNY/CCNY); I. Moroz (Oxford), E. Titi (UC Irvine).

Post-doctoral associates: H. Carlson, Guang Yang, Mohammed Rahibe, Erik Christensen.

Students: J. Gibson, Wing Ma, Peter Blossey, Berengere Podvin, Shaojie Tang, Zhijian Zhou.

6. Publications.

a) Research papers **published** duiring the report period:

Berkooz, G., Elezgaray, J., Holmes, P. J., Lumley, J. L. and Poje, A. 1994. The proper orthogonal decomposition, wavelets and modal approaches to the dynamics of coherent structures. *Applied Scientific Research* 53:321-338.

Berkooz, G., Holmes, P., Aubry, N., Lumley, J. L. & Stone, E. 1994. Observations regarding "Coherence and chaos in a model of the turbulent boundary layer"(by X. Zhou & L. Sirovich). *Physics of Fluids*, 6: 1574-1578.

Carlson, H. A. 1995. *Direct Numerical Simulation of Laminar and Turbulent Flow in a Channel with Complex, Time-Dependent Wall Geometries*. Ph. D. Thesis. Ithaca, NY: Cornell.

Coller, B. D. 1995. *Suppression of Heteroclinic Bursts in Boundary Layer Models*. Ph. D. Thesis. Ithaca, NY: Cornell.

Coller, B.D., Holmes, P. and Lumley, J.L. 1994 Control of bursting in boundary layer models. *Mechanics USA 1994 (Applied Mech. Rev.)* 47: S139-S143.

Coller, B.D., Holmes, P. and Lumley, J.L. 1994._Interaction of adjacent bursts in the wall region. *Phys. Fluids* 6 : 954-961.

Coller, B.D., Holmes, P. and Lumley, J.L. 1994. Controlling noisy heteroclinic cycles. *Physica D* 72: 135-160.

Cox, S. M. and Leibovich, S. 1994. Evolution equations for large-scale two-dimensional Langmuir circulation and double-diffusive convection. *J. Fluid Mech.* 276: 189--210.

Kribus, A. and Leibovich, S. 1994. Instability of strongly nonlinear waves in vortex flows, *J. Fluid Mech* 269: 247--264.

Lumley, J. L. 1994. Technical Evaluation Report, in *Application of Direct and Large Eddy Simulation to Transition and Turbulence*. AGARD-CP-551. pp. T-1-T-4. NATO: AGARD.

Poje, A. C., & Lumley, J. L. 1994. A model for large scale structures in turbulent shear flows. *J. Fluid Mech.* 285: 349-369.

Shih, T.-H., Shabbir, A. and Lumley, J.L. 1994. *Realizability in Second Moment Turbulence Closures Revisited* NASA TM 106469.

Shih, T.-H., Zhu, J. and Lumley, J.L. 1994. *Modeling of Wall-Bounded Complex Flows and Free Shear Flows*, NASA TM 106513.

Tandon, A. and Leibovich, S. 1995. Secondary instabilities in Langmuir circulation, *J. Phys. Ocean.* 25: 1206--1217.

b) Research reports during the report period (not in print yet, under review, etc.)

Aubry, N., Berkooz, G., Coller, B., Elezgaray, J., Holmes, P. J., Lumley, J. L. and Poje, A. 1995. Low dimensional models, wavelet transforms and control. In *Eddy structure identification techniques for free turbulent flows* , ed. J.-P. Bonnet. Heidelberg, etc.: Springer. In Press.

Berkooz, G., Elezgaray, J., Holmes, P. J., Lumley, J. L., Poje, A. and Volte, C. 1995. Fundamental aspects of incompressible and compressible turbulent flows. In *Turbulent flow modeling and prediction* , ed. T. Gatski. Heidelberg, etc.: Springer. In press.

Berkooz, G., Titi, E. S., Lumley, J. L. and Gibson, J. 1995.
Well-posedness for Spatially Localized Models of Fluid Flow. To be submitted.

Bradshaw, P., Launder, B. E. & Lumley, J. L. 1993. Collaborative testing of turbulence models. *J. Fluids Engineering*, XXX:XXX-XXX.

Carlson, H. A. and Lumley, J. L. 1995. Flow over an emerging obstacle. *AIAA J.* Submitted.

Carlson, H. A., Berkooz, G. and Lumley, J. L. 1996. Direct numerical simulation of flow in a channel with complex, time-dependent wall geometries: a pseudospectral method *J. Computational Physics.* In press.

Carlson, H. A. and Lumley, J. L. 1996. Active control in the turbulent boundary layer of a minimal flow unit. *J. Fluid Mech.* Submitted.

Dankowicz, H., Holmes, P., Berkooz, G. and Elezgaray, J. 1995. Local models of spatio-temporally complex fields. Corrected for final submission.

Holmes, P. J., Lumley, J. L and Berkooz, G. 1996. *Turbulence, Coherent Structures, Symmetry and Dynamical Systems.* Cambridge, UK: University Press. In Press.

Lumley, J. L., Acrivos, A., Leal, G. and Leibovich, S. (eds) 1996. *Research Trends in Fluid Dynamics* Woodbury, NJ: AIP Press. In press.

Myers, M., Holmes, P., Elezgaray, J. and Berkooz, G. 1995. Wavelet Projections of the Kuramoto-Sivashinsky Equation I: Heteroclinic Cycles and Modulated Traveling Waves for Short Systems. *Physica D.* XXX: XX-XX. In press.

Tandon, A. and Leibovich, S. 1995. Simulations of three--dimensional Langmuir circulation in water of constant density. *J. Geophys. Res.* In Press.

Shih, T.-H., Zhu, J. and Lumley, J.L. 1994. *A New Reynolds Stress Algebraic Equation Model*, NASA TM 106644. Accepted by *Comput. Methods Appl. Mech. Eng.*

7. Interactions / Transitions.

Dietmar Rempfer of the University of Stuttgart (Germany) is collaborating with us; he will join us for a three year period as a Visiting Assistant Professor with the support of a German Government Fellowship. Irene Moroz of Oxford University (UK) visits us every summer, and works with our students during the school year, by e-mail. Edris Titi of UC/Irvine visits us nearly every siummer, and works with Gal Berkooz during the school year. Nadine Aubry of CUNY/CCNY is spending her sabbatical year with our group, from August, 1995. In addition, we are in contact with Bud Lakshminarayana of the Gas Turbine Laboratory of the Pennsylvania State University. In collaboration with these personnel, we are exploring various control possibilities, developing various turbulence models which we anticipate will ultimately be helpful in predicting stage losses and heat transfer in compressor and turbine blade passages in axial flow turbomachines, and examining various mathematical questions arising in these connections.

G. Berkooz participated in the following meetings, where he gave the talks indicated:

Society of Engineering Sciences, Oct. 1994. Title: "Estimation and Control of Models of the turbulent wall layer".

ASME World Meeting, Nov. 1994.
Title: "Estimation and Control of Models of the turbulent wall layer".

SIAM Dynamical systems meeting, May, 1995. Symposium organizer: Dynamical Systems in Control of Fluid Flows: A University/Industry Perspective.
Talk: Application of dynamical systems to jet control.

G. Berkooz took part in the following discussions:

Met with Dr. Myers of UTRC to explain the ideas of dynamical systems approach and how they may be applied to turbine control.

Discussed with Wright Pat - IHPTET program the possibility of using the POD to resolve dynamical phenomena of multiple scales in blade heat transfer.

Discussed with Jeff Cipola of the Underwater warfare center the application of dynamical systems to control noise generating coherent structures in submarine flows.

In addition, we call ettention to the following transitions:

NASA is exploring through a contract to Lockheed and BEAM Technologies the possibility of using feedback control based on the dynamical systems ideas.

The experimental branch at NASA Langley is considering making an award for a tool to apply the dynamical systems concepts by less trained experimentalists.

BEAM is developing software that will automate key aspects of model generation for analysis and control purposes.

8. New discoveries, inventions, patent disclosures, etc.

None.

9. Honors / Awards

a) During this grant period:

Lumley: 1996 Dryden Lectureship in Research

b) Lifetime achievement honors:

Lumley:

Haute Distinction Honoris Causa - Ecole Central de Lyon, 1987.
Fellow, American Academy of Arts and Sciences.
Member, National Academy of Engineering.
Timoshenko Medal, American Society of Mechanical Engineers, 1993
AIAA Fluid and Plasmadynamics Award, 1982.
APS Fluid Dynamics Prize, 1990.
Fellow, APS.
Associate Fellow, AIAA.

Leibovich:

Member, National Academy of Engineering, 1993.
Fellow, American Academy of Arts and Sciences, 1992.
Fellow, American Society of Mechanical Engineers, 1985.
Fellow, American Physical Society, 1982.
Ohio Aerospace Institute Distinguished Lecturer, August, 1994