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Investigation of wall bounded turbulence:

Coherence and chaos in a model of turbulent boundary-layer

The dynamics of coherent structures in the wall region of a turbulent channel flow is considered. The Karhunen-Loeve eigenfunctions and Galerkin procedure are used to derive the dynamical description. In a previous treatment of this problem by Aubry *et al*[1] the analysis required an inhomogeneous pressure term to be supplied from outside the theory. In the first part of this paper this theory is reconsidered on the basis of the construction of wall eigenfunctions that have a full channel validity. As a result of the methods developed here, a well-posed Hermitian theory is developed and convergence questions do not arise. Among a number of important consequences is the fact that no exterior pressure is required by the present theory. In the second part of this paper it is shown that the behavior of the resulting model equations include intermittency, quasiperiodic and chaotic solutions. In the final portion part of this paper three dimensional effects are introduced into the dynamics in order to produce a physically more realistic dynamical theory. It is felt that the bursting and ejection events in turbulent boundary-layers is given a more satisfactory explanation within this framework.

Modeling No-Slip Flow Boundary with an External Force Field

A novel technique related to Peskin's immersed boundary approach [21-25] is used to introduce solid surfaces into a simulated flow field. The Navier Stokes equations permit the presence of an externally imposed body force that may vary in space and time. Forces are chosen to lie along a desired surface and to have a magnitude and direction opposing the local flow such that the flow is brought to rest at an element of the surface. For unsteady viscous flow the direct calculation of the needed force is facilitated by a feedback scheme in which the velocity is used to iteratively determine the desired value. In particular, we determine the surface body force from the relation

$\mathbf{f}(\mathbf{x}_s, t) = \alpha \int_0^t \mathbf{U}(\mathbf{x}_s, t')dt' + \beta \mathbf{U}(\mathbf{x}_s, t)$ for surface points $\mathbf{x}_s$, velocity $\mathbf{U}$, time t and negative constants α and β. Examples are presented which include 2D flow around cylinders, 3D turbulent channel flow where one boundary is simulated with a force field, and turbulent channel flow over a riblet covered surface. While the new method may be applied to complex geometries on a non-Cartesian mesh, we have chosen to use a simple Cartesian grid. All simulations are done with a spectral code in a single computational domain without any mapping of the mesh.

Drag Reduction in Turbulent Channel Flow by Phase Randomization

We present results of numerical simulations of plane turbulent channel flow in which we introduce a forcing which derives from the randomization of selected Fourier modes. In all cases, the randomization is introduced uniformly throughout the channel. The properties of the resulting turbulence are strongly dependent on both the wavenumbers whose phases are randomized and the forcing frequency. Two principal wavenumber bands have been selected. The first includes a selected subset of the largest length scales of the turbulence. Forcing in this band results in a fully sustained maximum mass flux increase above that of normal turbulence of 30 percent which translates into a drag reduction of 58 percent. Many of the statistical properties of the simulated drag reduced turbulence generated in this manner are in good qualitative agreement with the statistical properties of turbulence observed in experiments in which drag reduction is achieved through the introduction of small concentrations of long-chained polymers into the flow. In a second set of simulations, the phases of the intermediate and smallest wavelengths were randomized. Forcing at these scales of motion results in a drag increase. Speculations on the mechanism of the drag reduction by phase randomization are offered.

Papers in Referred Journals:

1. L. Sirovich, Analysis of turbulent flows by means of the empirical eigenfunctions, *Fluid Dynamics Research*, **8**, 85-100 (1991).

2. L. Sirovich and R. Everson, Management and analysis of large scientific datasets, *The International Journal of Supercomputer Applications*, **6**(1), 50-68 (1992).

3. D. Goldstein, Discrete-velocity collision dynamics for polyatomic molecules, *Phys. Fluids A* **4**(8), 1831-1839 (1992).

4. X. Zhou and L. Sirovich, Coherence and chaos in a model of turbulent boundary-layer, To Appear: Physics of Fluids (1992).

5. D. Goldstein, R. Handler and L. Sirovich, Modeling no-slip flow boundary with an external force field, To Appear: Journal of computational Physics.

6. R.A. Handler, E. Levich and L. Sirovich, Drag reduction in turbulent channel flow by phase randomization, Submitted: Phys. of Fluids.

Invited Presentations

National and International Meetings

October, 1992	Invited Speaker SIAM Conference on Application of Dynamical Systems Snowbird, Utah
April, 1992	Invited Speaker National Academy of Science Washington, DC
July, 1991	Invited Speaker ICIAM Washington, D.C.
May, 1991	Keynote Speaker American Geophysical Society Baltimore, MD

May, 1991	Workshop on Dynamics of Structures and Intermittencies in Turbulence Arizona State University Tempe, Arizona

Invited Colloquia

Argonne National Laboratory	June, 1992
University of Tel Aviv	May, 1992
Courant Institute	April, 1992
Colorado State University	April, 1991
MIT	April, 1991

Presentations

American Physical Society 44th Annual Meeting of the Division of Fluid Dynamics, November 24-26, 1991, Arizona State University, Scottsdale, Arizona

1. Dynamics of the Free Shear Flow Coherent Structures - M. Rajaee (Brown University), S. Karlsson (Brown University) and L. Sirovich (Brown University).

2. Eigenfunction Analysis of Turbulent Mixing Phenomena - L. Sirovich (Brown University), T.J. Barber (United Technologies Research Center), R.M. Everson (Brown University) and M. Winter (United Technologies Research Center).

3. Flow Boundaries Simulated with an External Force Field - D.B. Goldstein (Brown University), R.A. Handler (Naval Research Lab) and L. Sirovich (Brown University).

4. The Stability of Finite Amplitude Three-Dimensional Disturbances in Axisymmetric Pipe Flow - P. O'Sullivan (Brown University), K.S. Breuer (MIT) and L. Sirovich (Brown University).
5. Wave Structures in Wall-Bounded Turbulent flow - X. Zhou (Brown University) and L. Sirovich (Brown University).
6. A Simulation of Drag Reduction in Turbulent Channel Flow - R.A. Handler (Naval Research Laboratory), E. Levich (Levich Center, ORMAT Industries) and L. Sirovich (Brown University).

Awards/Honors/Prizes

Lawrence Sirovich, Brown Univesity, Fellowship from the American Physical Society.

Lawrence Sirovich, Brown Univesity, Byron Short Lecturer at the University of Texas.