Current Trends in Turbulence Research

Edited by
Herman Branover, Michael Mond,
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Preface

This volume contains a collection of papers devoted to modern trends in the research of turbulence, presented at the Fifth Beer-Sheva International Seminar on MHD Flows and Turbulence.

The Beer-Sheva Seminars have been held every three years since 1975, when a group of researchers from different countries, interested in both MHD flows and different aspects of turbulence in electroconductive fluids as well as nonconductive fluids, came together for a week-long seminar. All participants felt that the meeting was very fruitful in detecting promising areas of research and in developing new ideas. Therefore, the seminar was repeated in 1978 and ultimately became an ongoing event, taking place once every three years. It also became a tradition to publish the papers presented at the Beer-Sheva Seminar after a thorough review and editing. The first two volumes were published by John Wiley and Sons and the subsequent two by AIAA (volumes 84 and 100 in the *Progress in Astronautics and Aeronautics* series).

The Beer-Sheva Seminars became well known in the international scientific community and the number of researchers willing to participate kept growing steadily. This forced the organizers, who desired to preserve the special intimate atmosphere of the seminars and to keep very substantial time for informal discussions, to introduce ever more severe criteria in the paper-selection process. The intention was to keep the number of participants in each event below 100. The fifth Seminar, held during March 1987, hosted 99 participants from 12 countries. The number of papers which passed all the reviews reached 60, which is many more than those at previous seminars. In addition, a number of invited review papers were presented. It was therefore decided, for the first time, to publish the papers on MHD and on turbulence in two volumes.

The papers of the present *Turbulence* volume cover most of the important contemporary trends in both experimental and theoretical turbulence research, and give a concise and comprehensive picture of the present status in most of the areas in which extensive studies are going on. The authors of most of the articles in this volume are recognized leaders in turbulence research.

To better acquaint the reader on the content of the volume we will briefly describe here several experimental and several theoretical papers.

Hussain et al analyzes a number of fundamental issues related to the phenomenon of coherent structures in turbulent flows,the nature, and role. He stresses the point that although virtually every turbulence researcher pursued coherent structures in one form or another, there is yet no consensus on what these structures are, and what is their significance. Most opinions are based on flow visualization, which is at best qualitative, and sometimes misleading. The authors' opinion is that direct flow measurements (by a rake of cross hot wires or by more recently evolving techniques) and direct numerical simulation can throw much light on the whole coherent-structures problem. The present paper, as well as other works of the authors, are based on the definition of a coherent structure as an advected flow module in a turbulent flow characterized by instantaneously phase-correlated vorticity over its spatial extent.

Fiedler et al address the problem of amalgamation (or "pairing") of vortices and its role in lateral transport of momentum across the mixing layer. Stability theory accounting for the mean-flow divergence, and encompassing some weakly nonlinear effects, is able to predict many important features associated with large coherent structures in free turbulent shear flows. The linear model, for example, predicts the transverse distribution of amplitudes and phases of externally imposed wavy disturbances. The amplification rate in the streamwise direction can also be correctly predicted by the addition of some nonlinear terms. However, the special dynamical significance of vortex amalgamation seemingly suggested by experimental evidence, is not explainable by wave theory. The authors conclude that this stems from the fact that a photograph of tagged particles represents streaklines, which depend on the time and location of the tagging relative to the time and location of the observation.

Sukoriansky and Branover investigate experimentally and theoretically turbulent duct flows with clearly expressed inverse energy transfer. This phenomenon occurs in electroconductive fluids under the influence of a transverse magnetic field when energy is injected into the disturbed movement at high wave-number values. The onset of an inverse energy transfer corresponds to the conditions at which turbulence becomes strongly anisotropic owing to elongation of turbulent structures in the magnetic-field direction. All this occurs against the background of suppression of shear turbulence generation, and ultimately large-scale distrubances are strongly enhanced. Experimental clarification of the phenomena leading to the inversion of the turbulent energy transfer and to the enhancement of large-scale turbulence permitted the development of a theory based on the renormalization-group method. This theory enables the calculation of mean-flow characteristics without using empirical correlations. Flows with enhanced turbulence also possess enhanced and anisotrophic heat-transfer properties, as was proven both theoretically and experimentally.

N'Guyen Duc et al present an experimental study of two-dimensional flows consisting of a thin horizontal layer of mercury subject to a strong vertical magnetic field which both generates the flow by interactions with injected electric currents at the bottom of the box and stabilizes it with respect to three-dimensional disturbances. The instantaneous velocity field is obtained by visualizing the trajectories of small particles. It is also measured at 63 points simultaneously and analyzed. A $k^{-5/3}$ energy spectrum is obtained and interpreted as the inverse cascade observed on the visualizations.

Moffat reviews his recently developed topological approach to problems of vortex dynamics and turbulence, based on regarding a turbulent flow as an evolution of a dynamical system in a function space, the fixed points of which acquire special significance. These fixed points are steady Euler flows, characterized by ergodic blobs of maximal helicity, separated by stream-vortex surfaces, generally of toroidal topology, on which vortex sheets may be located. Kelvin Helmholtz instability of these vortex sheets gives rise to spiral structures that can in principle account both for an inertial-range spectrum of fractional exponent and the entrophy increase characteristic of three-dimensional turbulence.

Reshotko presents a review of problems of stability and transition to turbulence in boundary layers. He emphasized the continuing importance of linear stability theory in predicting transition, due account being taken of the level and character of various perturbing influences (free-stream turbulence, radiated sound, surface vibrations, etc.). He refers to the recent work of Ashpis, involving asymptotic solution of the nonhomogeneous (forced) Orr-Sommerfeld equation that reveals the emergence of Tolmein-Schlichting waves in response to controlled forcing by a vibrating ribbon. The linear regime is now understood to the extent that disturbances may be controlled (e.g., the wave produced by a vibrating ribbon may be cancelled by a second vibrating ribbon), and drag may thereby be reduced. By contrast, the so-called "bypass" phenomenon, involving large initial disturbances and essentially nonlinear effects are still not well understood.

Frisch et al report on a new large-scale instability, the so-called Anisotropic Kinetic Alpha effect, which is analogous to the the alpha-effect of MHD, and occurs in three-dimensional, anisotropic, incompressible flows lacking parity invariance. A specific example is given which leads to the growth of a very strong large-scale Beltrami flow where nonlinear saturation of the instability is obtained by feedback on the small-scale flow.

Kraichnan reviews several approaches to analytical turbulence theory. He gives special attention to relationships among (1) approximation by finite sets of moments, (2) renormalized perturbation theory (3) decimation under symmetry constraints, (4) renormalization-group methods, and (5) upper bounding of transport under integral constraints. The procedure of decimation under symmetry constraints, as mentioned by the author, has close connections with other approaches and play a unifying role.

Yakhot et al present an overview of the recently developed dynamic renormalization-group (RNG) method for hydrodynamic turbulence. The values of the important constants (Kolmogorov constant, turbulent Prandtl number, Batchelor constant, the von Kármán constant, and skewness factor) derived by RNG analysis are found to be in good agreement with experimentally obtained values. The results of calculations using an RNG-based k-ϵ transport model (heat transfer in a pipe and a pipe pulsating flow) are analyzed; the comparison with experimental data exhibits very good agreement.

Without going into detail, we should mention here that a number of papers deal with results of direct numerical simulation of both hydrodynamic and magnetohydrodynamic turbulence.

In their totality, the papers referred to above, together with many papers not mentioned here, present quite a complete picture of the contemporary trends in turbulence research as well as a substantial amount of the most recent results. The extensive references given in most papers of this volume should be an additional aid to the reader who wishes to make himself familiar with the status of the field.

The authors and editors are very pleased that the AIAA Progress Series is continuing to publish the proceedings of the Beer-Sheva International Seminars on MHD Flows and Turbulence.

The editors would like to express their gratitude to Martin Summerfield, Editor-in-Chief of the AIAA *Progress in Astronautics and Aeronautics* series for his continuing enthusiastic interest in the Beer-Sheva Seminars, and to Jeanne Godette, Managing Editor of the Progress Series, for her meticulous assistance.

We now look forward to the next volumes of this series, and we invite the reader to participate in the Sixth Beer-Sheva International Seminar on MHD Flows and Turbulence, which is planned for the early spring of 1990.

Herman Branover
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August 1988

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Coherent Structures: Their Measurements and Applications

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Introduction

Turbulence researchers' search for *order in disorder* has led to the discovery of large-scale organized motions in flows previously regarded as completely random. Popularly known as *coherent structures*, these large-scale motions have modified our perceptions of fluid turbulence, provided new tools for a better understanding of the physics of turbulence, and opened the door to the technologically interesting field of *turbulence management* -- both suppression and enhancement of turbulence phenomena, such as transports of heat, mass, and momentum; combustion and chemical reaction; and generation of aerodynamic noise and drag. In spite of the apparent ubiquity of organized structures in transitional and turbulent flows and the frantic study by virtually every turbulence researcher, our knowledge about these structures is extremely meager. Little is known about the topology and dynamical significance of coherent structures. Far less clear is the prospect for the incorporation of this new concept into a viable turbulence theory.

Coherent structures have been the focus of numerous studies, including a large number of review papers (notably, Kline et al.;[1] Crow and Champagne;[2] Winant and Browand;[3] Roshko;[4] Kovasznay;[5] Cantwell;[6] Lumley;[7] Coles;[8,9] Wallace;[10] Fiedler[11]). Most of the coherent structure studies have been based on flow visualization, which, though useful in transitional flows, is seldom instructive in fully turbulent states because of rapid diffusion of

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flow markers. Flow visualization can even be misleading in situations where there is a large mismatch of vorticity diffusivity and molecular diffusivity of flow markers (i.e., for large Schmidt number) so that sufficiently after tagging, the marker boundary has little to do with structure boundary.[12] In order to obtain any understanding of the dynamical significance of coherent structures, quantitative data are needed. What little data have been taken to address coherent structures have involved single-point measurements of velocity, pressure, temperature, or intermittency. In these studies, the primary focus was the mere demonstration of the existence of organized -- even periodic -- events in various flows, especially in the transitional regions, where the structures are typically fairly regular and thus more obvious than in the fully turbulent regions. Conclusions regarding the existence of organized structures were based either on spectral analyses or time-mean correlations. Measurements involving velocity, pressure, or intermittency also have limitations: a high correlation of velocity or pressure can arise in a flow without involving any vortical motion. Less useful are single-point measurements. Clearly, flow visualization and/or single-point measurements cannot unambiguously detect coherent structures, let alone address their characteristics and dynamical significance. It is our contention that vorticity is crucial to coherent structure studies, as will be discussed later.

With the advent of supercomputers, it is now possible to compute time evolution of velocity and pressure fields in turbulent flows via direct numerical simulations of the full Navier-Stokes equations at moderate Reynolds numbers and via large-eddy simulations at high Reynolds numbers (e.g., Moin and Kim;[13] Grinstein et al.;[14] Metcalfe et al.[15]). Velocity data can also be acquired from a turbulent flowfield using various measurement techniques, such as (multiple) hot-wire anemometry, particle displacement velocimetry, pulsed laser holographic velocimetry, and scanning laser Doppler anemometry. However, turbulence physics cannot be gleaned from such enormous volumes of apparently random data; coherent structures provide a framework for synthesizing the data. We need a precise operational definition, based on which coherent structures can be identified without any ambiguity and their dynamical significance assessed.

Because a unique feature of turbulent flows is three-dimensional random vorticity fluctuations, it is logical to identify coherent structures in terms of the vorticity field. Thus, a coherent structure is defined as *a connected*