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Studies of the Structure of Turbulence by High-Resolution Simulation and Theory

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The project was a study of structures of fluid turbulence using high-resolution direct numerical simulation and the theory development based on observations and measurements on the numerical simulations. Significant advances have been made in the study of fundamental fluid turbulence through numerical and theoretical work. The research has been focussed on the following areas: (1) The dynamics of advected passive scalar: Using the equations of motion, we analytically predict the anomalous scaling exponents for a passive scalar advected by fluid turbulence. The exponents are verified through large-scale simulation with 8192^2 mesh points. This is the first case in which anomalous scaling exponents for a turbulence problem have been deduced from the equations of motion. (2) The inertial range scaling in three-dimensional (3D) turbulence: High-resolution direct numerical simulations of 3D Navier-Stokes turbulence with normal viscosity and hyperviscosity are carried out to study the inertial-range statistics. It is found that both the scalings and the probability distribution functions are independent of the dissipation mechanism, but the near-dissipation-range fluctuations show significant structural differences; (3) Statistics and structures of pressure field, vorticity, and dissipation in three-dimensional incompressible isotropic turbulence have been studied. The statistical relations among pressure, vorticity, dissipation, and kinetic energy are investigated using a conditional averaging process; (4) The refined similarity hypothesis: We studied the conditionally averaged velocity increments as a function of the locally averaged dissipation. Our results provide direct evidence in support of the refined similarity hypotheses. The dimensionless averaged velocity increments $(\Delta u^n | \epsilon_r) / (\epsilon_r r)^{n/3}$ are found to depend on the local Reynolds number $Re_{\epsilon_r} = \epsilon_r^{1/3} r^{4/3} / \nu$ in a manner consistent with the refined similarity hypotheses.

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1. Background and Research Objectives

Turbulence, "the last unsolved in classical statistical mechanics" (Feynman), has been with us over 100 years since Reynolds found the laminar-turbulent transition in 1883. During this entire century, turbulence has been a great challenge for both theory and computation. For practical applications, people use idealized, highly parameterized turbulent modeling with arbitrary assumptions. Although the mechanisms of turbulence usually are poorly represented in these models and the values of the model parameters must be obtained empirically, such models are widely used and have great impact in diverse applied problems, such as engine and aerofoil design and global circulation models. On the other hand, theoreticians study turbulence as a stochastic dynamic system and try to relate the basic physical phenomena in turbulent flows to the underlying equations of motion. One of the hopes of this fundamental research is that it will provide insights into how to improve turbulence modeling.

The difficulties in physical understanding and modeling of fluid turbulence arise from fundamental dynamical properties: strong nonlinearity; the simultaneous presence and interaction of a huge number of degrees of freedom, comprising a wide range of spatial scales; and marked departure from absolute statistical equilibrium. More than 10^{18} degrees of freedom can be excited in turbulent flows typical of atmospheric phenomena. this makes full computer simulation of the flow impossible.

The phenomenon of intermittency is ubiquitous in turbulent flows. Intermittency is associated with the apparently random formation and disappearance of coherent structures, such as vortex tubes or regions of laminar flow, in a broader regime of disordered fluctuations. Intermittency characterizes both production (generation of turbulence by mean-flow variation) and the small-scale fluctuations that result from energy cascade from the larger scales. It is the consequence of nonlinearity and statistical disequilibrium. It can be observed in turbulent flows everywhere, from unstable combustion flame fronts to the atmospheric boundary layer. But the mechanisms of structure formation and their dynamical consequences are still unclear. Understanding of these phenomena is an essential ingredient in placing engineering models of turbulence on a sound basis. The usual parameterized models totally ignore intermittency effects and, in fact, use only the most primitive statistics of the turbulence. This raises two questions: Why do the models work as well as they do? Can they be improved economically by inclusion of more realistic statistics?

Theoretical approaches for turbulence based on deduction from the equations of motion have mostly involved field-theoretic techniques of renormalized perturbation

theory. The direct-interaction approximation (DIA) is the prototypical example. Because they are perturbative, such theories are unsuited for prediction of the higher statistics, such as probability distribution functions (PDFs) that are indicators and measures of structure formation and intermittency.

A novel theoretical approach, called mapping closure, has been originated at Los alamos National Laboratory. The new and key feature of the mapping closure is direct handling of PDFs in physical space, rather than the use of moments in wave-vector space and perturbation expansions as in traditional statistical theories of turbulence. The basic idea in the mapping closure is to approximate an actual turbulent field by tractable nonlinear transformations, or mappings, of a Gaussian reference field. The method has been applied successfully to the relaxation of an initially non-Gaussian scalar field under the heat equation, the evolution of Burgers turbulence, and the statistics of a temperature field that suffers both random advection and molecular diffusion.

Direct numerical simulation has become a powerful tool for the study of turbulence. Recent improvements in computer memory and speed, and especially the availability of well-integrated, massively parallel machines, have made computer simulation a necessary supplement to laboratory experiments. Concurrently, faster and more powerful graphics processing has become feasible. At present, laboratory experiments can reach higher Reynolds numbers (more degrees of freedom) than simulations, but simulations offer more precise control of parameters and more complete data sets. The latter are an impetus toward the development of new interactive visualization techniques to aid in the identification and understanding of flow structures.

This research was intended to bring together a suite of computational and theoretical tools to provide a coherent and unified attack on the problem of structure and intermittency in turbulence and turbulent chemical reactions. A unified approach is crucial because each component provides needed strengths and capabilities. The numerical simulations at high resolution will not only provide basic understanding of turbulence phenomena, but also provide important data bases for testing and development of the theoretical analysis. Conversely, the theory development will guide the numerical work and illuminate the phenomena observed in simulations.

2. Importance to LANL's Science and Technology and National R&D Needs

Turbulence is of universal importance in fluid flows. Its correct description thereby impacts such diverse fields as atmospheric pollutant dispersion, weather, commercial chemical processes, aircraft design, ship design, and ocean dynamics. Within

statistical physics, turbulence is a prime example of a complicated nonlinear system in a state of statistical disequilibrium. Improved turbulence codes are important both for their application to fields such as those named and for the insight they can provide, in partnership with theory, into the fundamental dynamics of turbulence. Turbulence theories such as the mapping technique used in the present work are important in two ways: they can lead to improved parametrization of turbulent transport coefficients in applications and they can help sort out which dynamical features of turbulence are essential to the phenomenon.

Several important ongoing projects at LANL, including the ocean circulation model, the atmospheric climate model, chemical-reacting systems and fluidized-bed simulations, are using turbulent models. The research proposed here will provide some insight for these problems and may help put the models in these problems on a more solid basis.

The research supported by this LDRD has important impacts on the turbulence research in the US. The paper by Kraichnan on anomalous scaling exponents has inspired a huge research interest and led to over two dozen papers over the past two years, including numerical simulations and analysis of experiments. The three-dimensional (3D) turbulence simulation data generated at Los Alamos have been the base for researchers all over the country. A dozen scientific papers, coauthored with faculty members from a variety of university and industrial researchers, have been written based on our simulation results.

3. Scientific Approach and Results

The principal theoretical tool has been the mapping closure method which allows us to construct nonperturbative ansatz which connects the two point dissipation function with the temperature increment. The theory has been partially proved mathematically and verified through direct numerical simulation. The fundamental goal of the development of the mapping closure and the related ansatz has been to approximate the effects of nonlinear dynamics on velocity and advected scalar fields by simple and tractable mappings of Gaussian reference fields.

Turbulence analysis has been dominated for a long time by traditional approaches, based on low-order statistics. A newly emerging approach focusing on structures of turbulent flows has been inspired by the modern development of massively parallel computers and three dimensional visualization capability. Turbulence at high Reynolds number usually includes a very large number of degrees of freedom, with the result that

statistical statements are the natural way to express global characteristics. But turbulence is a nonlinear dynamic system in which statistical information represents the ensemble average of explicit structures whose individual behavior depends on the equation of motion and specific boundary conditions. Statistics such as moments or PDFs tell little about how the individual structures look or behave.

The computational part of this research has been focused on the study of relations between statistics and the structure of turbulence. We have carried out the following steps in numerical simulations:

1. Adaptation of existing simulation codes to new requirements. We have further improved the performance by moving the high-performance Fortran code to a low-level message-passing code.
2. A visualization code based on Data Explorer has been developed. Using this tool, we are able to identify and specify the 3D structures of vorticity and dissipation and the passive scalar field.

Here we present some highlights:

- The advection of a passive scalar field by a rapidly decorrelating random velocity field with power law scaling is computed by simulations in a cyclic square at resolutions of 4096^2 and 8192^2 points. Various statistics of the scalar field, including inertial-range scaling exponents, are analyzed and compared with some theoretical predictions.
- High-resolution direct numerical simulation data for three-dimensional Navier-Stokes turbulence in a periodic box are used to study the scaling behavior of low-order velocity structure functions with positive and negative powers. Like the high-order statistics, the low-order relative scaling exponents exhibit unambiguous departures from the Kolmogorov 1941 theory and agree well with existing multiscaling models. No transition from normal scaling to anomalous scaling is observed.
- Properties of velocity circulation in three-dimensional turbulence are studied using data from high-resolution direct numerical simulation of Navier-Stokes equations. The probability density function (PDF) of the circulation depends on the area of the closed contour for which circulation is calculated, but not on the shape of the contour. For contours lying within the inertial range, the PDF has a Gaussian core with conspicuous exponential tails, indicating that intermittency plays an important

role in circulation statistics. The measured scaling exponents are anomalous and substantially smaller than those implied by Kolmogorov's phenomenology.

- We apply She and Leveque's hierarchy model under the assumption that $\lim_{p \rightarrow \infty} \tau_p/p = 1$ with τ_p being the p -th order scaling exponent for the local averaged dissipation function suggested by Novikov. The resulting model agrees well with existing theoretical and experimental results for $p \leq 10$. The most interesting prediction of this model is the cut-off of the exponents of the p -th order moments of velocity increments as $p \rightarrow \infty$.
- High-resolution direct numerical simulations of three-dimensional Navier-Stokes turbulence with normal viscosity and hyperviscosity are carried out. It is found that the inertial-range statistics both the scalings and the PDFs, are independent of the dissipation mechanism, but the near-dissipation-range fluctuations show significant structural differences. Nevertheless, the relative scalings expressing the dependence of the moments at different orders are universal, and show unambiguous departure from the Kolmogorov 1941 description, including the 2/3 law for the kinetic energy. Implications for numerical modeling of turbulence are discussed.
- Statistics and structures of pressure in three-dimensional incompressible isotropic turbulence are studied using high-resolution direct numerical simulation for Taylor microscale Reynolds numbers up to 220. It is found that the probability distribution function of pressure has negative skewness as a result of both kinematic and dynamic effects directly connected with statistical properties of the pressure head. The statistical relations among pressure, vorticity, dissipation, and kinetic energy are investigated using a conditional averaging process. The averaged pressure, conditional on the local enstrophy, shows a linear dependence on enstrophy in the high enstrophy region. Relations between various physical quantities and pressure amplitudes are elucidated by three-dimensional visualization. Quantitative spatial relations of these quantities in high- and low-pressure regions are shown. It is suggested that experimental visualization techniques for detecting high-intensity vortices using microbubbles in low-pressure regions might only be valid for very high-vorticity regions where the local enstrophy is more than five times higher than the root mean square enstrophy. The scaling law of the pressure structure function is also presented in terms of both conventional and extended self-similarity. It is demonstrated that extended self-similarity can give a better pressure scaling relation.

- The fundamental hypotheses underlying Kolmogorov-Obukhov (1962) turbulence theory are examined *directly* and *quantitatively* by using high-resolution numerical turbulence fields. With the use of the massively parallel Connection Machine-5, we have performed direct numerical simulations (DNS) of Navier-Stokes flows at 512^3 resolution with Taylor microscale Reynolds numbers up to 219. Three very different types of flows are considered—free-decaying turbulence, stationary turbulence forced at a few large scales, and a 256^3 large-eddy simulation (LES) flow field. We demonstrate that both the forced DNS and LES flow fields show realistic inertial-subrange dynamics. The Kolmogorov constant for the $k^{-5/3}$ inertial-range energy spectrum obtained from the 512^3 DNS flow is in the range of 1.52 to 1.68. The probability distribution of locally averaged dissipation rate ϵ_r over a length scale R is nearly log-normal in the inertial subrange, but with significant departures in the tails. The intermittency parameter μ , appearing in Kolmogorov's third hypothesis for the variance of other logarithmic dissipation is found to be in the range of 0.20 to 0.28. The scaling exponents over both ϵ_r and r for the conditionally averaged velocity increments $\overline{\Delta u}/\epsilon_r$ are quantified, which provide direct evidence in support of the refined similarity hypotheses. The dimensionless average velocity increments $(\overline{\Delta u^n}|\epsilon_r)/(\epsilon_r r)^{n/3}$ are found to depend on the local Reynolds number $Re_{\epsilon_r} = \epsilon_r^{1/3} r^{4/3}/\nu$ in a manner consistent with the refined similarity hypotheses. In the inertial subrange, the probability distribution of $(\Delta u|\epsilon_r)/(\epsilon_r r)^{1/3}$ is found to be universal and have an exponential tail. Universal constants in the second Kolmogorov refined similarity hypothesis are determined quite accurately and found to increase with the order n at a faster-than-exponential rate. Finally, some consideration is given to the use of pseudo-dissipation in the context of the 1962 Kolmogorov theory where it is found that the results are not as good as those based on the true local dissipation.

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