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Progress in Turbulence VII

Proceedings of the iTi Conference in Turbulence 2016

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Editors

Progress in Turbulence VII

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Preface

The iTi has become an established biannual conference on turbulence research taking place in the years between the ETC—(European Turbulence Conference) and TSFP—(Turbulence and Shear Flow Phenomena) conferences. With 80 to 100 participants, the iTi conference places value on the discussions and personal contacts in the location of the beautiful town of Bertinoro in Northern Italy close to Bologna. It continues a tradition that has been started in Bad Zwischenahn/ Germany with the first edition of the conference in 2003. The size of the conference allows to have no parallel sessions and gives time to special topics to be stressed. The content-related focus areas of the conference are the interdisciplinary aspects of turbulence, defining the abbreviation iTi—interdisciplinary Turbulence initiative. iTi attracts scientist from the engineering, physics, and mathematics communities.

It has been a tradition of the iTi to organize a one-day workshop before the iTi conference on a distinct theme out of the wide spectrum of turbulence research. The present workshop was on*High Reynolds number turbulent flows—A large-scale infrastructure perspective*. The 7th iTi in 2016 conference hosted 90 scientists from 15 different countries. In total, there were 78 contributions, from which 50 were presented as talks, with six invited talks, covering a wide range of aspects of current turbulence research. Advances in the basics of understanding and modeling turbulence were addressed as well as practical implications such as the control of turbulence.

The content of the 7th iTi conference is documented in this volume comprising 35 contributions. All contributions were thoroughly reviewed by external reviewers, to whom we want to express our thanks for their valuable and important contribution. Both the workshop and conference were sponsored by the European High-performance Infrastructures in Turbulence (EuHIT). EuHIT is an international scientific mobility programme for researchers engaged in turbulence research (www.euhit.org).

Based on the successful previous conferences, we will continue with this initiative for subsequent years with the 8th iTi Conference planned for September 2018.

Stockholm, Sweden	Ramis Örlü
Forlì, Italy	Alessandro Talamelli
Darmstadt, Germany	Martin Oberlack
Oldenburg, Germany	Joachim Peinke
2017	

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Part I

Theory

Emergence of Non-Gaussianity in Turbulence

Michael Wilczek, Dimitar G. Vlaykov and Cristian C. Lalescu

Abstract Fully developed turbulence is characterized by markedly non-Gaussian statistics. Here, we discuss some aspects of the relation between non-Gaussianity, the emergence of coherent structures and phase correlations in turbulence. Direct numerical simulations of homogeneous isotropic turbulence are used to demonstrate a fairly rapid emergence of non-Gaussian statistics from Gaussian initial conditions.

1 Introduction

One hallmark of fully developed turbulent flows is the intrinsic non-Gaussianity of the velocity field. For example, the single-point probability density function (PDF) of the velocity, which characterizes the large scales, remains close to Gaussian with slightly sub-Gaussian tails [1, 2]. The PDFs of small-scale quantities such as the vorticity, however, exhibit broad tails. This translates to the frequent occurrence of extreme events and is a signature of small-scale coherent structures such as vortex tubes or strain sheets. In comparison, Gaussian fields, whose multi-point statistics are jointly Gaussian, appear largely structureless.

Velocity increment PDFs effectively interpolate between the small- and large-scale statistics. Using them to probe turbulent velocity fields on increasing scales reveals a breaking of statistical self-similarity: the PDFs change shape as a function of scale. This well-known phenomenon of intermittency is absent in Gaussian fields, which are statistically self-similar. This motivates the question of how non-Gaussianity and intermittency arise from the turbulent dynamics.

In the following we give a qualitative discussion on the relation between non-Gaussian statistics and the emergence of coherent structures and phase correlations in turbulence. In particular, we study the evolution of a turbulent flow from Gaussian

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initial conditions by means of direct numerical simulations. Finally, we outline how these insights may be useful to better understand and model intermittency in turbulence.

2 Direct Numerical Simulations and Gaussian Initial Conditions

We present direct numerical simulations (DNS) of statistically stationary homogeneous isotropic turbulence at a Taylor-based Reynolds number of $R_\lambda \approx 129$. A standard pseudo-spectral solver is used to simulate the Navier–Stokes equation in the vorticity formulation in a periodic box with 512^3 grid points at a resolution of $k_M \eta_K \approx 1.67$, where k_M denotes the highest resolved mode and η_K the Kolmogorov length. The flow is forced on the large scales by a term linear in the band-passed vorticity (Lundgren forcing) [3, 4]. Time-stepping is performed with a third-order memory-saving Runge–Kutta method [5].

To generate Gaussian initial conditions, a snapshot from the simulation is taken from the statistically stationary regime. The Fourier coefficients $\mathbf{u}(\mathbf{k})$ are rotated in the complex plane, $\mathbf{u}(\mathbf{k}) \rightarrow \mathbf{u}(\mathbf{k})\, \mathrm{e}^{\mathrm{i}\varphi(\mathbf{k})}$, with statistically independent random phases $\varphi(\mathbf{k})$, which are uniformly distributed in $[0, 2\pi]$ for each $\mathbf{k}$. Reality of the velocity field is imposed by ensuring $\varphi(\mathbf{k}) = -\varphi(-\mathbf{k})$. As will be clarified in Sect. 4, the resulting velocity field is close to Gaussian. Seventeen distinct realizations of $\varphi(\mathbf{k})$ are used, such that an ensemble of approximately Gaussian fields is obtained. These fields are then taken as initial conditions for new DNSs, the results of which are discussed in the following sections.

3 Emergence of Non-Gaussian Statistics

A qualitative impression of the DNS results with approximately Gaussian initial conditions can be gained from Fig. 1, which shows visualizations of the velocity and vorticity fields for three subsequent instances in time. The fact that Gaussian initial conditions appear structureless is particularly evident in the vorticity visualizations. As the flow evolves under the Navier–Stokes dynamics, small-scale coherent structures start to emerge rapidly. Already after ten Kolmogorov time scales (characterizing the fastest turbulent dynamics) they can be clearly identified. The fine-scale structure of the velocity field changes on a comparable time scale. However, its large-scale structure changes only slowly. The difference between the two fields is understood through a simple eddy turnover argument by considering that the velocity is a large-scale and the vorticity a small-scale quantity.

Quantitatively, consider the single-point PDFs for the velocity and vorticity fields (Fig. 2). The velocity PDF is initially close to Gaussian with slightly sub-Gaussian tails. The deviations can be explained by the fact that the initial velocity field is steeper than k^{-1}, which leads to corrections to the behavior expected from a central limit

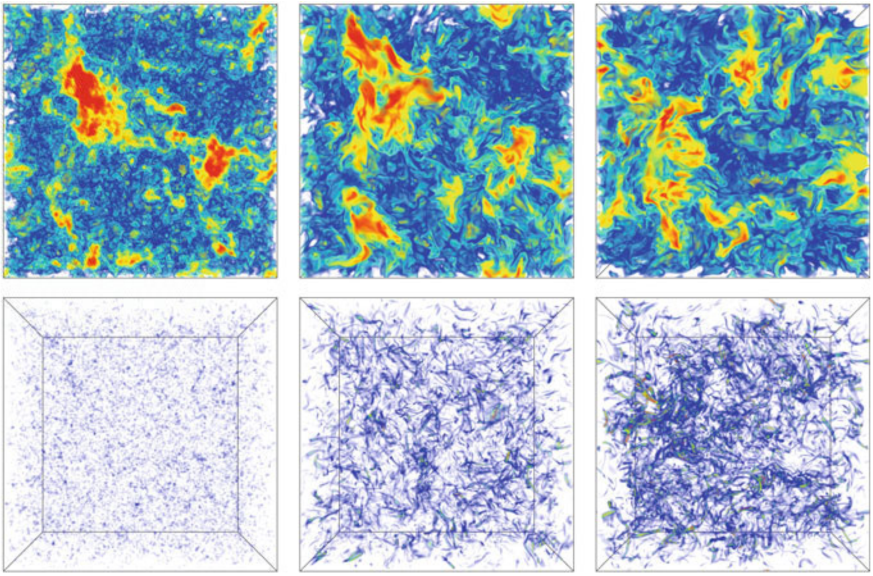

Fig. 1 Snapshots of DNS velocity fields (*top row*) and vorticity fields (*bottom row*) at simulation times of approximately 0, 10, 100 Kolmogorov time scales. Already after ten Kolmogorov time scales small-scale vorticity structures have emerged, and they grow stronger over time. Also the fine-scale structure of the velocity field changes, whereas large-scale features remain qualitatively similar

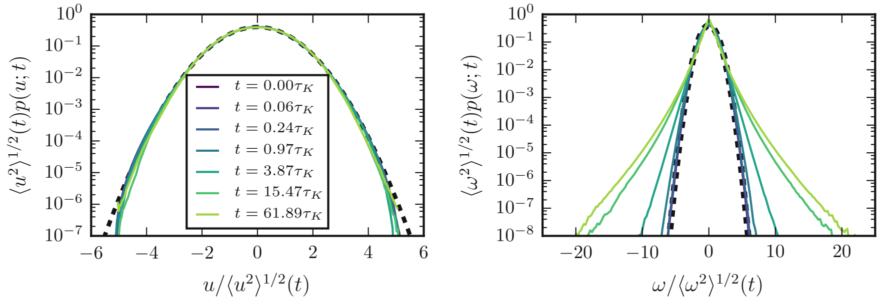

Fig. 2 One-point PDFs for velocity and vorticity fields. The velocity PDFs are slightly sub-Gaussian throughout the evolution. The vorticity PDFs start out as Gaussian, but quickly deviate and settle into a strongly non-Gaussian form

theorem argument [6]. As the field evolves from these initial conditions, the velocity PDF varies slightly due to the temporal evolution of fluctuations, but remains very close to Gaussian as expected from previous theoretical considerations [7]. Along with the emergence of small-scale coherent structures, the vorticity PDF rapidly develops heavy tails [8]. This nicely visualizes the common picture of turbulence, in which small-scale coherent structures break statistical self-similarity and therefore contribute to non-Gaussianity and intermittency.

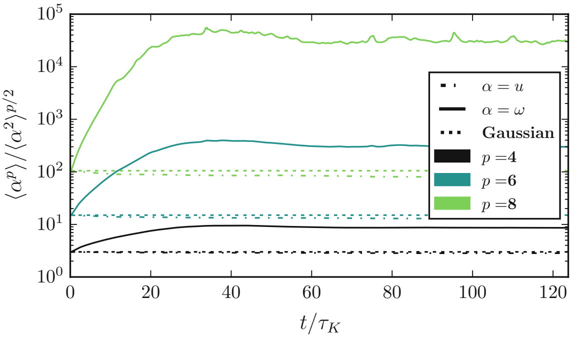

Fig. 3 Time evolution (in units of the Kolmogorov time τ_K) of the normalized moments of the velocity field (*dash-dot*) and the vorticity field (*solid*). While for the velocity field the values remain slightly sub-Gaussian, the vorticity quickly exhibits strong non-Gaussianity. Gaussian values are shown as *dashed lines* for reference

The emergence of non-Gaussian statistics from Gaussian initial conditions can also be confirmed by studying moments of the velocity and vorticity fields as a function of time, as presented in Fig. 3. As can be seen, the single-point moments of the velocity field stay close to the Gaussian values. Consistent with the observations of the vorticity PDF, the single-point vorticity moments rapidly depart from their Gaussian initial values.

4 Phase Correlations

There is an intimate relation between Gaussianity and phase correlations. For a Gaussian random field different Fourier modes are mutually statistically independent. One should note that this is a much stronger statement (as it pertains to all statistical moments) than the fact that for homogeneous random fields the phases are uncorrelated (which concerns only second-order moments). As mentioned above, the opposite also holds: A superposition of Fourier amplitudes with random phases results in approximately Gaussian statistics under quite general conditions (see e.g. [9]). Thus phase correlations are a signature of non-Gaussian statistics.

To explain the emergence of phase correlations, it is instructive to consider the well-known Fourier representation of the Navier–Stokes equations for the amplitude $a_l(\mathbf{k}, t)$ and the phase $\varphi_l(\mathbf{k}, t)$:

$$\begin{aligned}\left(\partial_t + \nu k^2\right) a_l(\mathbf{k}) &= \frac{1}{2}\sum_{m,n} P_{lmn}(\mathbf{k}) \sum_{\mathbf{p}+\mathbf{q}=\mathbf{k}} a_m(\mathbf{p})a_n(\mathbf{q}) \sin\left[\varphi_m(\mathbf{p}) + \varphi_n(\mathbf{q}) - \varphi_l(\mathbf{k})\right] \\ -a_l(\mathbf{k})\, \partial_t \varphi_l(\mathbf{k}) &= \frac{1}{2}\sum_{m,n} P_{lmn}(\mathbf{k}) \sum_{\mathbf{p}+\mathbf{q}=\mathbf{k}} a_m(\mathbf{p})a_n(\mathbf{q}) \cos\left[\varphi_m(\mathbf{p}) + \varphi_n(\mathbf{q}) - \varphi_l(\mathbf{k})\right] .\end{aligned} \quad (1)$$

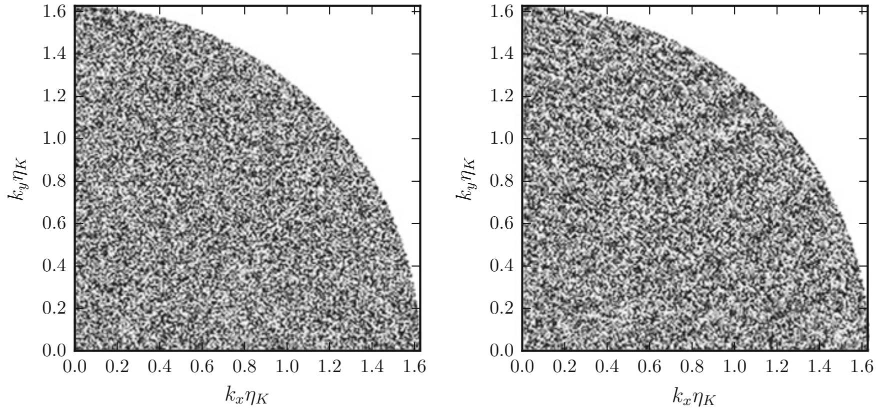

Fig. 4 Phases of one component of the velocity field in the $k_z\eta_K = 0$ plane. The *left plot* shows the phases for one of the Gaussian initial conditions, while the *right plot* shows the phases for the same velocity field after the quasi-stationary regime has been reached

Here, $P_{lmn}(\mathbf{k}) = k_m P_{ln}(\mathbf{k}) + k_n P_{lm}(\mathbf{k})$ is a suitably defined projection operator based on $P_{lm}(\mathbf{k}) = \delta_{lm} - \frac{k_l k_m}{k^2}$ [10]. It is interesting to note that the linear (viscous) term does not impact the phase dynamics directly. In contrast, the nonlinear term couples phase triads of Fourier coefficients which fulfill $\mathbf{k} = \mathbf{p} + \mathbf{q}$. This coupled phase dynamics then gives rise to correlations among phases.

Figure 4 shows the phases of a single velocity component in the $k_z\eta_K = 0$ plane. The left panel corresponds to the close to Gaussian initial conditions. By construction, all of the phases are statistically independent. The right panel shows the phases after approximately $76\tau_K$. As expected for turbulence, the phases are more or less random, however there is a remarkable degree of visual coherence, especially at smaller scales, with approximately equidistant striations visible in the "1 o'clock" region of the quadrant.

5 Conclusion and Outlook

By investigating numerical simulations of fully developed turbulence from approximately Gaussian initial conditions, we have seen that small-scale statistics (like the vorticity PDF) rapidly transition to non-Gaussianity whereas the large scales (exemplified by the single-point velocity PDF) remain close to Gaussian. In Fourier space, this is accompanied by the emergence of phase correlations, which appear more pronounced at smaller scales. Combining these two observations, our current working hypothesis is that intermittency in turbulence can be interpreted in terms of scale-dependent phase correlations. Due to the complexity of the Navier–Stokes equations, it remains a formidable task for future work to derive first-principle results on such phase correlations.

Meanwhile, it may turn out to be useful to study toy models. For example, one may consider the temporal evolution of a one-dimensional periodic field with the Fourier representation $u(x,t) = \sum_k a(k) \mathrm{e}^{\mathrm{i}[\varphi(k,t)+kx]}$. Assuming that the amplitudes remain fixed in time, one can impose a phase dynamics reminiscent of the Navier–Stokes dynamics (1):

$$\dot{\varphi}(k) = \sum_{p=-N}^{N} \omega(k,p) \cos\left[\varphi(p) + \varphi(k-p) - \varphi(k)\right] \tag{2}$$

where $\omega(k,p) = -\frac{k a(p) a(k-p)}{a(k)}$ are coupling coefficients depending on the prescribed Fourier amplitudes. Note that this phase coupling model is even simpler than the one-dimensional Burgers equation, as the amplitudes here are time-independent. We refer to [11] for an analysis of the phase dynamics in the one-dimensional Burgers equation. First numerical results indeed confirm that the phase coupling model (2) displays phase correlations which are more pronounced at smaller scales. As a consequence, small-scale statistics of the resulting field in real space depart more strongly from Gaussianity than large-scale statistics. Such toy models could also be useful in the modeling of intermittency, their simplicity inviting more direct analytical approaches. It is interesting to note that the phase coupling model establishes a relation to the field of non-locally coupled oscillators which are known to display a plethora of dynamical states including phase synchronization, chaos and chimera states. It will be exciting to see to which extent such concepts also apply to the phase dynamics of turbulence.

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Percolation: Statistical Description of a Spatial and Temporal Highly Resolved Boundary Layer Transition

Tom T. B. Wester, Dominik Traphan, Gerd Gülker and Joachim Peinke

Abstract In this article spatio-temporally resolved particle image velocimetry data of a flat plate's boundary layer are shown. With this set up, it is possible to capture the highly unsteady phase transition from laminar to turbulent state of the boundary layer close to the surface. In the evaluation of the boundary layer data it is shown that it is possible to link the laminar-turbulent phase transition to the (2+1)D directed percolation universality class. This can be shown by the unique exponents of the directed percolation class which will be extracted from the PIV data.

1 Introduction

The description of transition into turbulence has always been a challenging task. Thirty years ago Pomeau was the first to describe the dynamics of laminar-turbulent transition by a system of coupled oscillators [1]. Thereby he paved the way for the statistical description of laminar-turbulent transition by the directed percolation theory. This theory allows a simple description of complex phase transitions with only three critical exponents. These exponents are unique for each universality class of percolation, so the transition from a laminar to a turbulent flat plate's boundary layer may be ascribed to a known class.

Until the last decade it was not possible to provide experimental evidence to show the spatio-temporal intermittency which occurs in the transition from laminar to turbulent flow. Due to more accurate measurement techniques nowadays it is possible to capture the transition with much higher temporal and spatial resolution.

This has led to more detailed investigations with respect to directed percolation of different flow situations such as channel flow [2, 3], Couette flow [4], shear flows [5–8] and fully turbulent flows [9]. All of them show promising results, which support the presumption of Pomeau.

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