# DY 32: Focus Session: Statistics of fully developed turbulence

Despite its omnipresence and wide range of technical applications, a comprehensive understanding of fully developed turbulence remains elusive. Fully developed turbulence constitutes a paradigm of a complex system with a large number of strongly interacting degrees of freedom far from equilibrium. With coherent structures interacting in a complex manner, fully developed turbulence falls in between purely random and pattern-forming systems. It is this combination which makes it a challenging research field with connections to non-equilibrium statistical mechanics, pattern formation and stochastic processes. In this focus session we will cover various aspects of fundamental turbulence research from both the Eulerian and Lagrangian perspective. (Organizors M.Wilczek and O. Kamps)

Time: Wednesday 15:00–18:45 Location: BH-N 243

**Invited Talk** DY 32.1 Wed 15:00 BH-N 243

**Turbulence and Instantons** — Tobias Grafke[1], •Rainer Grauer[2], Tobias Schäfer[3], Stephan Schindel[2], and Eric Vanden-Eijnden[4] — [1]Dept. of Physics of Complex Systems, Weizmann Institute, Rehovot, Israel — [2]Theor. Physik I, Ruhr-Universität Bochum, Bochum, Germany — [3]Dept. of Math., College of Staten Island, CUNY, USA — [4]Courant Institute, NYU, New York, USA

It is evident that coherent nearly singular structures play a dominant role in understanding the anomalous scaling behavior in turbulent systems.

We ask the question, which role these singular structures play in turbulence statistics. More than 15 years ago, for certain turbulent systems the door for attacking this issue was opened by getting access to the probability density function to rare and strong fluctuations by the instanton approach. We address the question whether one can identify instantons in direct numerical simulations of the stochastically driven Burgers equation. For this purpose, we first solve the instanton equations using the Chernykh-Stepanov method [2001]. These results are then compared to direct numerical simulations by introducing a filtering technique to extract prescribed rare events from massive data sets of realizations.

In addition, we solve the issue why earlier simulations by Gotoh [1999] were in disagreement with the asymptotic prediction of the instanton method and demonstrate that this approach is capable to describe the probability distribution of velocity differences for various Reynolds numbers.

DY 32.2 Wed 15:30 BH-N 243

**The non-universality of magnetohydrodynamic turbulence** — •Wolf-Christian Müller[1], Roland Grappin[2], Andrea Verdini[3], and Özgur Gürcan[4] — [1]Technische Hochschule Berlin, Plasma-Astrophysik — [2]LUTH, Observatoire de Paris and LPP, Ecole Polytechnique, France — [3]Università di Firenze, Dipartimento di Fisica e Astronomia, Firenze, Italy and Royal Observatory of Belgium, SIDC/STCE, Brussels — [4]LPP, Ecole Polytechnique, Paris, France

We present a new cascade scenario motivated by the three-dimensional energy spectrum observed in numerical simulations of incompressible MHD turbulence in a strong mean field. It is shown that the energy distribution is not in accord with standard critical balance and the associated scale anisotropy. In spite of this, a measurable anisotropy of structure-function scaling exists independent of taking spatial increments with respect to the mean or local direction of the magnetic field.

We, thus, propose a combination of weak Iroshnikov-Kraichnan dynamics governing energy transfer in the field-perpendicular plane and the ricochet process distributing energy quasi-resonantly along all other directions. This spectral transfer process asymptotically approaches the 2D IK-cascade as $B_0$ increases. The new transfer mechanism is at variance with the commonly accepted resonant weak-turbulence cascade as well as with the critically balanced strong turbulence cascade. It is shown that the non-universal spectral dynamics are determined by the large-scale ratio of kinetic and magnetic energy.

DY 32.3 Wed 15:45 BH-N 243

**Markov closure for the Lundgren-Monin-Novikov hierarchy in turbulence** — •Jan Friedrich and Rainer Grauer — Institut für theoretische Physik I, Ruhr-Universität Bochum, Deutschland

A central, yet unsolved problem of hydrodynamic turbulence is the closure problem, which is due to the nonlinear character of the Navier-Stokes equation. We formulate the closure problem for the many-increment probability distributions and introduce a new method for closing the hierarchy. Here we use the experimental and numerically verified assumption that the turbulent cascade possesses a Markov property in scale [1] down to the so-called Einstein-Markov length. This approximation is far beyond a Gaussian approximation and allows a full description of intermittency effects. The procedure is explained on the example of the simpler Burgers equation corresponding to a fluid without pressure contributions whose singular structures are determined by so-called shocks. The proposed closure also opens up the way to a perturbative treatment of the Navier-Stokes equation beyond the Einstein-Markov length in successively taking into account a larger and larger scale "history" of the system.

[1] R. Friedrich, J. Peinke, Phys. Rev. Lett. 78 (5) (1997) 863-866

DY 32.4 Wed 16:00 BH-N 243

**Stochastic description of a turbulent wake** — •Nico Reinke and Joachim Peinke — ForWind, Institute of Physics, Carl v. Ossietzky University, Oldenburg, Germany

The presentation will give an insight in our experimental work to fractal generated turbulent flows and especially in the stochastic analysis of this turbulent flow. The stochastic approach allows to characterize the turbulent cascade process in scale $r$ and in different distances $x$ to the grid. This stochastic characterization shows the complexity of the flow and the transition between an non homogenous to a homogenous turbulent flow. To characterize the wake of a fractal grid velocity measurements $v(t)$ (using hot wire anemometer) were performed on the wind tunnel test section center line $x \rightarrow v(t,x)$. We analysis the wake in terms of velocity increments $u(r,x) = v(t + \frac{r}{<v>}, x) - v(t,x)$. The velocity increments are consider as Markov chain, which is true for $r \geq l_{EM}$, where $l_{EM}$ is the Einstein-Markov coherence length. The information of the turbulent cascade process is captured in the conditional probability distribution function $p(u(r,x)|u(r+\delta r,x))$, $\delta r \geq l_{EM}$. $p(u(r,x)|u(r+\delta r,x))$ changes for different scales $r$. This change is describe by the so called Fokker-Planck equation, which is governed by Kramers-Moyal functions $D^{(1)}(u(r,x))$ and $D^{(2)}(u(r,x))$. Finally, those functions characterize the turbulent cascade and allow us to understand the wake in scale and in distance to the grid.

DY 32.5 Wed 16:15 BH-N 243

**Stochastic analysis of aerodynamic forces acting on airfoils in turbulent inflow** — •Gerrit Kampers[1], Michael Hölling[1], Ulrike Cordes[2], Klaus Hufnagel[2], Cameron Tropea[2], and Joachim Peinke[1] — [1]ForWind, Institute of Physics, University of Oldenburg, 26111 Oldenburg, Germany — [2]Institute of Fluid Mechanics and Aerodynamics, Technical University of Darmstadt, 64287 Darmstadt, Germany

Wind turbines work within the atmospheric boundary layer, which is dominated by turbulence. Such turbulent flows feature non-Gaussian statistics, that are currently not accounted for by industry standards. These intermittent statistics lead to heavy fluctuations in aerodynamic forces and mechanical loads, respectively. Active and passive flow control elements represent a promising approach for the reduction of fluctuating loads.

We present a new testing method for wind tunnel experiments, that allows an investigation of the force fluctuations on airfoil segments with and without flow control elements under realistic and reproducible conditions. The statistics of the desired inflow are defined by a scale dependent analysis of offshore wind data and then reproduced in the wind tunnel with an active grid. Aerodynamic quantities of interest are measured and subsequently studied using a stochastic Langevin approach, which separates the deterministic response of a system from its stochastic (noisy) part. This method enables for a quantitative analysis of the dynamical performance of flow control mechanisms in turbulent conditions.

**15 min. break**

**Invited Talk** DY 32.6 Wed 16:45 BH-N 243

**Particle motion and irreversibility of turbulent flows** — •Alain Pumir[1,2], Haitao Xu[2], Jennifer Jucha[2], and Eberhard Bodenschatz[2] — [1]Laboratoire de Physique, Ecole Normale Superieure de Lyon, F-69007, Lyon, France — [2]Max-Planck Institut für Dynamik und Selbst-Organisation, D-37077, Göttingen, Germany

In three-dimensional turbulent flows, the flux of energy from large to small scales breaks time- reversal symmetry. I will discuss how this irreversibility can be observed by following the trajec- tories of tracers, moving with the fluid.

For the problem of relative particle dispersion, irreversibility implies that particles separate slower forward in time than backward (see Jucha et al, PRL 2014). This property can be understood in terms of an exact relation, established directly from the Navier-Stokes equations. A more surprising observation is that a tracer particle needs more time to build up large kinetic energy, than to dissipate it. This allows us to quantify the irreversibility of the turbulent fluid (Xu et al, PNAS, 2014).

DY 32.7 Wed 17:15 BH-N 243

**The Time Irreversibility of Turbulence** — •Jennifer Jucha[1], Alain Pumir[2], Haitao Xu[1], and Eberhard Bodenschatz[1] — [1]Max Planck Institut für Dynamik und Selbstorganisation, Göttingen, Deutschland — [2]Ecole Normale Supérieure, Lyon, Frankreich

The dissipation of energy at the smallest scales of a turbulent flow leads to an increase in entropy and therefore renders the flow time-irreversible. This irreversibility also influences the transport and mixing processes at larger scales of the flow but the connection was unclear so far. In this talk, an analytical relation between the dissipation process and the dispersion of particle clusters will be presented. Experimental and numerical results will be shown that confirm our theoretical approach.

DY 32.8 Wed 17:30 BH-N 243

**The stochastic description of non-Brownian particles in shear flow by a colored-noise Fokker-Planck equation** — •Laura Lukassen[1,2] and Martin Oberlack[1,2] — [1]Chair of Fluid Dynamics, TU Darmstadt — [2]Graduate School of Excellence Computational Engineering, TU Darmstadt

As described in literature, non-Brownian particles in shear flow show a diffusive behavior due to hydrodynamic interactions, namely shear-induced diffusion. The stochastic description by means of a Fokker-Planck equation is of major interest for non-Brownian particles in shear-induced diffusion. In contrast to Brownian diffusion, there is no separation of time scales in the context of shear-induced diffusion. The configuration of non-Brownian particles changes on the same time scale as the hydrodynamic velocity. This fact violates the Markov process assumption in pure position space. In order to assure the Markov process assumption, we derived a new Fokker-Planck equation in coupled position-velocity space (Lukassen, Oberlack, Phys. Rev. E 89, 2014). Under certain conditions, this new coupled Fokker-Planck approach can be reduced to a modified equation in pure position space. The new modified position space description exhibits additional correction terms when compared to other position space Fokker-Planck equations in that context known from literature. Our extended approach shall enable a better stochastic description of non-Brownian particle flows.

The work of L. Lukassen is supported by the "Excellence Initiative" of the German Federal and State Governments and the Graduate School of Computational Engineering at TU Darmstadt.

DY 32.9 Wed 17:45 BH-N 243

**Universal properties of the intermittency generating function in fully developed turbulence** — •Christoph Berling[1] and Oliver Kamps[2] — [1]Institut für Theoretische Physik, University of Münster, Germany — [2]Center for Nonlinear Science, University of Münster, Germany

The understanding of the intermittent fluctuations of observables in fully developed turbulence is one of the central challenges in turbulence research. One example for intermittency is the non-self-similar evolution of the probability density functions (PDFs) of the Lagrangian velocity increments $v(\tau, t) = u(t+\tau) - u(t)$ with respect to the time lag $\tau$. Based on the combination of an exact but unclosed PDF equation and experimental results it is possible to describe the non-self-similar evolution of the Lagrangian increment PDFs by a single function that itself is self-similar [1]. In this contribution we will show that within this framework Lagrangian intermittency can also be described for turbulent flows with different Reynolds numbers as well as for magneto-hydrodynamic and two-dimensional turbulence.

[1] Wilczek et. al., New Journal of Physics **15** (2013) 055015

DY 32.10 Wed 18:00 BH-N 243

**the intermittent behavior of DDES simulation of fractal-generated turbulence** — •Mohamed Cherif Mihoubi[1], Bernhard Stoevesandt[1], and Joachim Peinke[1,2] — [1]Fraunhofer Institute for Wind Energy and Energy System Technology IWES, Oldenburg, Germany — [2]ForWind, Center for Wind Energy Research, Oldenburg, Germany

In order to study the relevant sources of noise from wind turbines under real atmospheric inflow conditions, we investigate CFD simulations of fractal generated turbulence. The fractal grid used in this simulation is based on an experimental set-up to be able to validate the simulation results. The Results showed that in the production region of the turbulence the pdfs are roughly Gaussian, the deviation from the Gaussian distribution starts at 0.9 m and lasts up to 2 m behind the fractal grid. In this region the statistics show highly intermittent behavior with heavy tails which show similar behavior to atmospheric turbulence (please see [1],[2]). From 2 m on, the pdfs become Gaussian again. Additionally, energy spectrum, integral length scale and other quantities are evaluated on the stream-wise directions. In comparison with wind tunnel data, the effect of turbulence model in analyzed

[1] Morales, A., Wächter, M. and Peinke, J. (2012), Characterization of wind turbulence by higher-order statistics,*Wind Energ., 15: 391*406. doi: 10.1002/we.478*

[2] Mücke, T., Kleinhans, D. and Peinke, J. (2011), Atmospheric turbulence and its influence on the alternating loads on wind turbines, *Wind Energ., 14: 301*316. doi: 10.1002/we.422*

DY 32.11 Wed 18:15 BH-N 243

**Describing the heat transport of turbulent Rayleigh-Bénard convection by POD methods** — •Johannes Lülff — WWU Münster

Rayleigh-Bénard convection, which is the buoyancy-induced movement of a fluid enclosed between two horizontal plates, is an idealized setup to study thermal convection. We analyze the modes that transport the most heat between the plates by calculating the proper orthogonal decomposition (POD) of numerical data. Instead of the usual POD ansatz of finding modes that describe the energy best, we developed a method that is optimal in describing the heat transport. Thereby, we can determine the modes with the major influence on the heat transport and the coherent structures in the convection cell. We also show that in lower-dimensional projections of numerical convection data, the new developed modes perform consistently better than the standard modes.

DY 32.12 Wed 18:30 BH-N 243

**2d-LCA - a new highly resolving anemometer** — •Jaroslaw Puczylowski, Michael Hölling, and Joachim Peinke — University of Oldenburg / ForWind - Center for Wind Energy Research, Oldenburg, Germany

The 2d-Laser Cantilever Anemometer (2d-LCA) is a recently developed sensor for two-dimensional velocity measurements in fluids. It uses a mico-structured cantilever as a sensing element, which allows for extremely high resolved measurements. Hence, spatial structures of 140micrometer can be resolved at temporal resolutions of about 100kHz. The 2d-LCA can be applied in the same way as commercial x-wires, however, it can also be used in particle-laden flows and liquids. In addition, the angular acceptance range of the 2d-LCA comprises 90°, whereas standard x-wires are limited to 45°. Comparative measurements with the 2d-LCA and an x-wire have been carried out in a laboratory-generated turbulent wake flow. The data sets of both measurement techniques were analyzed using same stochastic methods. These include spectral analyses, inspection of velocity increments and analyses of extended self-similarity (ESS). Furthermore, key parameters, such as characteristic lengths, mean values of velocity and angles of attack were determined from both data sets. The evaluation shows great agreement between both anemometers. Therefore, we are able to show that the 2d-LCA is capable of providing data that is consistent with established sensors and theory.