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Rotation rate of particle pairs in homogeneous isotropic turbulence

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ABSTRACT

Understanding the dynamics of particles in turbulent flow is important in many environmental and industrial applications. In this paper, the statistics of particle pair orientation is numerically studied in homogeneous isotropic turbulent flow, with Taylor microscale Reynolds number of 300. It is shown that the Kolmogorov scaling fails to predict the observed probability density functions (PDFs) of the pair rotation rate and the higher order moments accurately. Therefore, a multifractal formalism is derived in order to include the intermittent behavior that is neglected in the Kolmogorov picture. The PDFs of finding the pairs at a given angular velocity for small relative separations reveal extreme events with stretched tails and high kurtosis values. Additionally, The PDFs are found to be less intermittent and follow a complementary error function distribution for larger separations.
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1. Introduction

Understanding how particles are advected by fluids is of major interest in many applications, including the environmental and the geophysical flows [1]. One outstanding example is the eruption of volcanoes, where particles with different sizes and inertia are released into the atmosphere [2] and then transported with turbulent currents [3,4]. In addition to the environmental importance of understanding the influence of turbulence on particle dispersion, this problem is also of practical interest in the industrial flows, where the advection of particles is involved [5,6].

The theoretical studies of the relative separation between two particles are based on stochastic models. Many experiments [7,8] and numerical simulations [9,10] have been performed over the last few decades in order to accurately evaluate these theories. Richardson, in his pioneering work [11], has examined the relative motion of particle pairs in turbulent flows. He has estimated the scale dependency of the eddy-diffusivity coefficient through the observation of dispersed plumes. This scale dependency is claimed to be the origin of the accelerated nature of turbulent dispersion [12]. In the inertial range of motion (for $\eta \ll r \ll L$ and $\tau_\eta \ll t \ll T_L$, where η is the Kolmogorov dissipative scale, L is the energy injection length scale of the flow, τ_η is the local-eddy-turn-over-time and T_L is the large time scale), Richardson has suggested that the process of relative dispersion is governed by a diffusion-like equation. Solving this equation gives the probability of finding a pair of particles at a specific separation, at any time [13]. Nevertheless, recent studies [14,15] on the dynamics of tracer pairs that are released from many point sources have reported severe deviations from the Richardson theory. Additionally, this theory does not account for the rotational behavior of particle pairs.

The orientation dynamics of a single rigid ellipsoid particle under Stokes flow has been described by Jeffery [16], where inertia and the thermal fluctuations are neglected. The same equation can be used to describe the motion of any axisymmetric particle, provided that its aspect ratio is known [17]. In the presence of weak inertia, Einarsson et al. [18,19] studied the rotation of small and neutrally buoyant axisymmetric particles in a viscous shear flow, by perturbatively solving the coupled particle-flow equations. Shin and Koch [20] presented the results of direct numerical simulations (DNS) of the translational and rotational motions of fibers in a fully developed isotropic turbulent flow, for a range of Reynolds numbers. They concluded that the fibers whose lengths are much smaller than the Kolmogorov length scale η translate like fluid particles and rotate like material lines. With increasing fiber length, the translational and rotational motions of the fibers slow down as they become insensitive to the smaller-scale eddies.

Using computer simulations, Pumir and Wilkinson [21] studied the temporal evolution of the orientation vector of microscopic rod-like particles. They showed that rod-like particles are more strongly aligned with vorticity than with the principal strain axis. An interesting component of turbulence, which is named the pirouette effect, has been reported by Xu et al. [22]. It has been

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Table 1
Parameters of the numerical simulation.

Kolmogorov dissipative active length scale η	0.005
Spacing between two collocation points in the regular cubic lattice Δx	0.006
Mean turbulent kinetic energy dissipation rate per unit mass ϵ	0.81
Fluid kinematic viscosity ν	0.00088
Dissipative time scale τ_η	0.033
Integral time scale T_L	67
Energy injection length L	2π
Number of collocation points N	1024
Turbulent velocity fluctuation u'	1.7

shown that the axis of rotation of tetrahedra tracers aligns with the initially strongest stretching direction, a phenomena which can be justified by the conservation of the angular momentum. Using video particle tracking technique, Parsa et al. [23] made accurate simultaneous measurements of the motion and the orientation of the rods in the presence of a bi-dimensional chaotic velocity field. The first three-dimensional experimental measurements of the orientation dynamics of rod-like particles was also reported by Parsa et al. [24]. In this work, a good agreement with the previous numerical simulations was reported. Moreover, Parsa and colleagues [25] studied the rotation rate of the rods with lengths in the inertial range of turbulence. They presented the experimental measurements of the rotational statistics of neutrally buoyant rods, and derived a scaling law for the mean-squared rotation rate. The latter showed a good agreement with the Kolmogorov classical scaling.

It is noteworthy that, to the best of our knowledge, the orientation of the tracer pairs has not been studied so far. Therefore, this question will be addressed here, by computing the probability of finding a pair of particles at a specific rotation rate, given the relative separation between them. By considering a particle pair with a specific separation, one can study the orientation statistics of an imaginary tracer rod that is delimited by these two particles. Furthermore, for the first time, the pair rotation rate PDFs at later times will be presented in this work.

This paper is organized as it follows. The next section describes the numerical data, and the approach that is used to derive the rotation rate of the tracer pairs. Afterward, the intermittency behavior that is observed at the small scales of motion is discussed in detail. In Section 3, the multifractal (MF) formalism to intercept the probability density function (PDF) distributions is presented. Thereafter, the higher-order moments of the rotation rate are evaluated and compared to the multifractal prediction together with the Kolmogorov (K41) picture. Finally, the concluding remarks, and the outlooks are stated in Section 4.

2. Methods

2.1. Particle pair orientation

The rotational dynamics of particle pairs in turbulent flow can be addressed by solving the dimensionless incompressible Navier–Stokes equations for a Newtonian fluid, i.e.

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}.\nabla\mathbf{u} = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2\mathbf{u} + \mathbf{f}, \tag{2.1}$$

$$\nabla.\mathbf{u} = 0, \tag{2.2}$$

using Direct Numerical Simulations (DNS). In these equations, $\mathbf{u}$ denotes the tri-dimensional velocity field, p is the pressure and Re is the flow Reynolds number, $\mathrm{Re} \equiv Lu'/\nu$. Re measures the ratio between the nonlinear inertial forces, and the linear viscous forces, where u' is the root-mean-squared velocity and ν is the fluid kinematic viscosity which is defined as the ratio between the dynamic molecular viscosity μ and, the fluid density ρ. In order to avoid energy dissipation, the flow was forced by keeping the total energy constant in the first wavenumber shells, by applying a large-scale forcing term $\mathbf{f}$. This force injects energy at a mean rate of $\epsilon = \langle \mathbf{f}.\mathbf{u}\rangle$, where ϵ is the mean turbulent kinetic energy dissipation rate [26]. The integration of the equations of motion is performed on 1024^3 regular cubic lattice with Taylor microscale Reynolds number of 300, and periodic boundary conditions. The simulation parameters are shown in Table 1. With the present choice of parameters, the dissipative range of length scales is well resolved because the grid size Δx is in the range of Kolmogorov length scale η (as it is reported in more detail by Biferale et al. [14]). A fully-de-aliased parallel pseudospectral code, with a second-order Adams–Bashforth temporal scheme, for 3D homogeneous isotropic turbulence, assuming constant fluid viscosity and density, is used in order to solve Eqs. (2.1) and (2.2).

The fluid is seeded with bunches of tracers emitted within a small region which has a size comparable to the Kolmogorov dissipative scale η. The emission is carried out in puffs of 2000 particles that are followed during a maximum time of 160 τ_η. The tracer particles take on the fluid velocity immediately, and adapt the rapid fluid velocity fluctuations [27]. Therefore, the velocity of each tracer is related to the instantaneous fluid velocity by the following equation:

$$\mathbf{v_p} \equiv \frac{d\mathbf{x_p}}{dt} = \mathbf{u}(\mathbf{x_p}(t), t). \tag{2.3}$$

The particle trajectories are computed by integrating Eq. (2.3). The positions and the velocities of each particle are stored at a sampling rate of τ_η. For the 2000 particles generated in each puff, all the possible pairs (approximately two millions) are considered [28].

2.2. Pair angular velocity

The pair angular velocity can be measured on the basis of the instantaneous positions and the velocities of the two particles. Consider a given pair of particles defined at every time by its separation vector $\mathbf{r}$ pointing from the first tracer particle toward the second one. One of the particles is taken as a reference point for computing the pair orientation. The relative velocity of the other particle $\Delta\mathbf{u}$ is decomposed into two components; i.e. $\Delta\mathbf{u}_\parallel$ parallel to the separation vector, and $\Delta\mathbf{u}_\perp$ perpendicular to it. The first particle and the transverse component of the relative velocity of the second one, defines a plane of rotation. The axis of rotation $\mathbf{e}$ is then normal to this plane, and defines the direction of the angular velocity pseudovector $\boldsymbol{\omega}$. By taking θ as the angle between the separation vector $\mathbf{r}$ and $\Delta\mathbf{u}$, then the angular velocity vector can be written as

$$\boldsymbol{\omega} = \frac{|\Delta\mathbf{u}_\perp|}{|\mathbf{r}|}\mathbf{e} = \frac{|\Delta\mathbf{u}|\sin\theta}{|\mathbf{r}|}\mathbf{e}, \tag{2.4}$$

or

$$\boldsymbol{\omega} = \frac{\mathbf{r}\times\Delta\mathbf{u}}{r^2} \tag{2.5}$$

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