EFFECT OF FLOW ANISOTROPY ON DISPERSION AND DISTRIBUTION OF PARTICLES

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Abstract We perform direct numerical simulations of strained turbulence laden with passive and inertial particles of varied inertia. We investigate the effect of large scale flow distortion due to straining, resulting in anisotropy ranging from the large scale down to the inertial range and the dissipative range, by studying particle acceleration statistics. A secondary objective is to understand the effects of weak straining on the distribution of particles in the fluid, by exploring the evolution of spatial distribution statistics and investigating particle dispersion from simple sources.

INTRODUCTION

Strained turbulence involving inertial particles is present in an assortment of practical engineering flows and in natural phenomena. This assortment includes flows in internal combustion engines and jet engines, flows in power plant components, and flows in the atmosphere, rivers, lakes and oceans where straining is induced by changes in geometry or fluid density. The bulk of work on inertial particles in turbulence has focused on approximately isotropic flows [1]. Recent studies have involved more complex flow geometries [3, 4, 5, 6], whose effects on particle statistics such as the particle acceleration probability density functions (PDFs) have been shown to be strong. In our simulations, we apply mean straining to introduce and maintain scale dependent anisotropy in the flow, and to quantify the effects on particles over a range of Stokes numbers.

METHOD

The equations describing the turbulent flow field, are the Navier-Stokes and the continuity equations:

$$\partial_t \tilde{\boldsymbol{u}} + \tilde{\boldsymbol{u}} \cdot \nabla \tilde{\boldsymbol{u}} + \nabla \tilde{p} = \nu \nabla^2 \tilde{\boldsymbol{u}}, \qquad \nabla \cdot \tilde{\boldsymbol{u}} = 0, \tag{1}$$

where $\tilde{\boldsymbol{u}}$ is the instantaneous velocity of the flow, $\tilde{p}$ is the instantaneous pressure, and ν is the kinematic viscosity of the fluid. The mean flow field, corresponding to axisymmetric expanding flow, is given by $U = (-2Sx, Sy, Sz)$, where S is the mean strain rate. We perform direct numerical simulation with Rogallo's algorithm [2] to simulate the strained flow.

The flow is seeded with small, heavy particles of varied inertia, at low seeding densities. The equations describing particle position and velocity are derived from the Stokes equations:

$$\frac{d\boldsymbol{x}_p}{dt} = \tilde{\boldsymbol{v}}_p, \qquad \frac{d\tilde{\boldsymbol{v}}_p}{dt} = \frac{1}{\tau_p}\left(\tilde{\boldsymbol{u}}(\boldsymbol{x}_p) - \tilde{\boldsymbol{v}}_p\right), \tag{2}$$

here, $\boldsymbol{x}_p$ and $\tilde{\boldsymbol{v}}_p$ refer to the particle position and velocity, $\tau_p = \beta d_p^2/18\nu$ is the Stokes relaxation time for the particle, where d_p is the particle diameter, $\beta = (\rho_p - \rho_f)/\rho_f$, and ρ_p, ρ_f are the particle and fluid densities, respectively. The Stokes number is defined as $\mathrm{St} \equiv \tau_\mathrm{p}/\tau_\eta$, where $\tau_\eta = 0.05$ is the Kolmogorov timescale of our flow.

For statistical convergence, we conduct 16 independent realizations of different strain rates. The flow and particle field are initialized isotropically prior to applying the strain. Simulations are performed in a lattice of $[1024, 256, 256]$.

RESULTS

In Figure 1, left, we measure the anisotropy of the flow via the ratio between transverse and longitudinal velocity structure functions. The ratio is a measure of the scale dependent anisotropy in the flow, the isotropic prediction is 2 for small r/η, and 4/3 for r/η in the inertial range.

The three right figures of Figure 1 show the PDFs of particle accelerations. The PDFs are based on particles initiated close to the symmetry planes $x = 0$ for the a_x component and $y = 0$ for the a_y component in order to reduce the effect of the mean flow. The Stokes number shown are calculated with respect to the Kolmogorov scale at the beginning of the straining. As the Stokes number increases, the PDFs appear to narrow due to the straining (very mildly for the low strain rate shown) in both the compression (x) and more so in the expanding (y) directions.

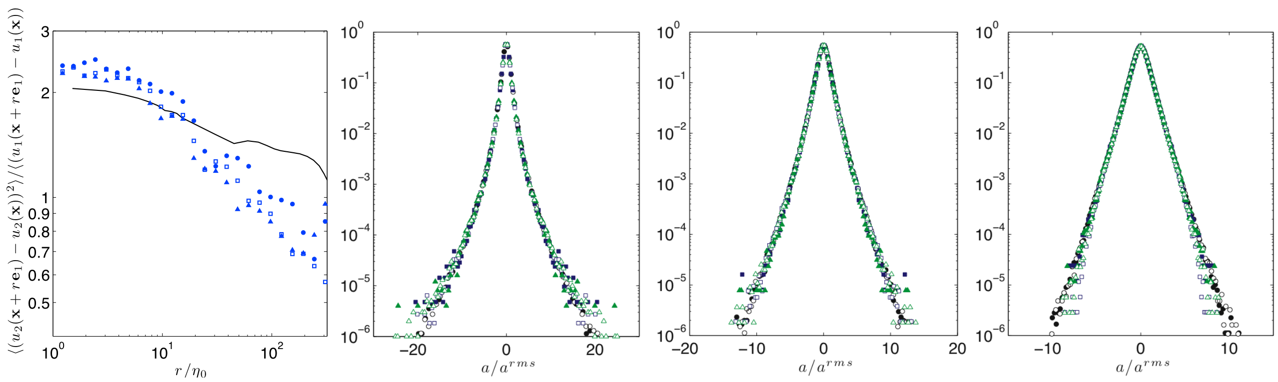

Figure 1. Left – Ratio of velocity structure functions for strain rate $S = 1$ at various time instants. Circle: $S \times t = 0.24$, square: $S \times t = 0.48$, triangle: $S \times t = 0.72$, line: HIT. Right – PDFs of particle acceleration for HIT and strain rate $S = 1$: tracer (left), St $= 0.3$(middle), St $= 1$(right). Black circle, blue square, green triangle markers represent strain-times $S \times t = 0(\text{HIT}), 0.248, 0.504$. Solid markers represent x-component PDFs, and empty markers represent y-component PDFs.

Dispersion of the inertial particles from plane sources are studied by investigating the ratios between their position variances and the tracers' position variances in Figure 2. We initiate particles in thin layers, centered on $x = 0$ (compression) and $y = 0$ (expansion) for the ratios $\langle x_p^2\rangle/\langle x_{\text{tracer}}^2\rangle$ and $\langle y_p^2\rangle/\langle y_{\text{tracer}}^2\rangle$ respectively. It is interesting to note that for all but the heaviest Stokes number considered, the dispersion of inertial particle initially tends to lead the tracer dispersion in the compression direction. In the expanding direction the particle position variances decrease from their HIT values and are smaller than the tracers position variances.

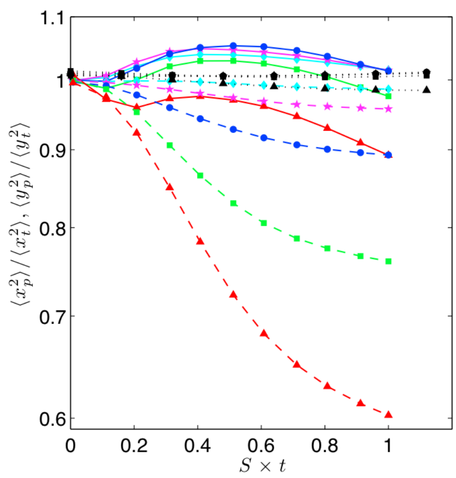

Figure 2. Dispersion of particles from plane sources. The solid lines are the $\langle x_p^2\rangle/\langle x_{\text{tracer}}^2\rangle$ ratios and the dashed lines are the $\langle y_p^2\rangle/\langle y_{\text{tracer}}^2\rangle$ ratios. Cyan diamond: St $= 0.2$, magenta pentagram: St $= 0.3$, blue circle: St $= 0.5$, green square: St $= 1$, red triangles: St $= 2$. Dotted-line black-marker curves: corresponding particle-tracer position variances ratios in HIT.

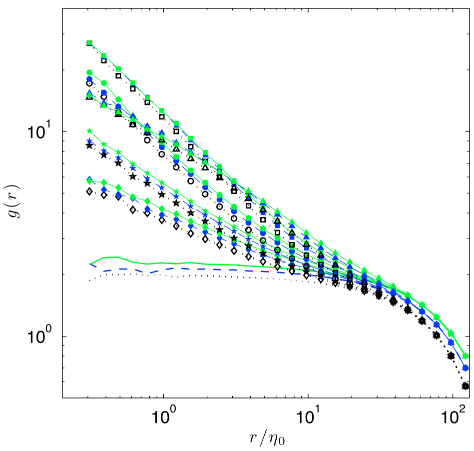

Figure 3. The RDF for HIT and for strain rate $S = 1$ at various time instants. Black dotted line, blue dashed line, green solid line represent $S \times t = 0(\text{HIT}), 0.16, 0.32$. Line only: tracers, diamond: St $= 0.2$, pentagram: St $= 0.3$, circle: St $= 0.5$, square: St $= 1$, triangle: St $= 2$.

Figure 3 shows the radial distribution function (RDF) at various stokes numbers. There straining appears to mildly increase the magnitude of the RDF with time, for the lower Stokes number particles.

References

[1] J. Bec et al: Acceleration statistics of heavy particles in turbulence. *J. Fluid Mech.* **550**:349–358, 2006.

[2] R. S. Rogallo: Numerical experiments in homogeneous turbulence. Tech. Rep. 81315, 1981.

[3] P. Gualtieri, F. Picano, and C. M. Casciola: Anisotropic clustering of inertial particles in homogeneous shear flow. *J. Fluis Mech.* **629**:25–39, 2009.

[4] V. Lavezzo, A. Soldadi, S. Gerashchenko, Z. Warhaft, and L. R. Collins On the role of gravity and shear on inertial particle accelerations in near-wall turbulence. *J. Fluis Mech.* **658**:229–246, 2010.

[5] S. Gerashchenko, N. S. Sharp, S. Neuscamman, and Z. Warhaft Lagrangian measurements of inertial particle accelerations in a turbulent boundary layer. *J. Fluis Mech.* **617**:255–281, 2008.

[6] G.H. Good, S. Gerashchenko, and Z. Warhaft Entrainment and mixing of water droplets across a shearless turbulent interface with and without gravitational effects *J. Fluis Mech.* **617**:293–303, 2011.