Divergence and rotation of inertial particles in a four-way coupled channel flow

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Abstract

Inertial particle data from three-dimensional direct numerical simulation of dilute, four-way coupled particle-laden turbulent channel flow at $Re_\tau \approx 230$ are analyzed. Modified Voronoi tessellation (Oujia *et al.* 2022) is applied to the particle positions considering a range of mass loading ($10\% - 100\%$) and particle inertia ($\mathrm{St}^+ \approx 1 - 7$). Using finite-time measures, we then quantify the divergence and rotation of the particle velocity (Oujia *et al.* 2022). Statistical analysis of divergence and curl are performed, along with their dependence on the wall distance, to assess the influence of the flow anisotropy. The probability distribution functions (PDFs) of the divergence and curl show that the particle inertia affects the tails of the PDFs (extreme events). Joint PDFs of the divergence and the volume cell further clarify if the divergence is most prominent in cluster regions or in void regions. The PDFs of the inertial particle vorticity deviate those of the fluid. The relationship with sweep and ejection motion of the particles is discussed.

Introduction

Wall-bounded turbulent flows containing small particles are relevant to numerous applications in engineering and nature, including solid rocket propulsion, and sediment transport in rivers. Many computational studies have previously examined aspects of particle-laden turbulent channel flow, including the role of collisions (Vreman *et al.* 2009) and particle Stokes number (Lee *et al.* 2015). The dynamics of inertial particles provide critical information on the flow; the divergence of the particle velocity quantifies void and cluster formation and the curl quantifies rotating motion. Voronoi tessellation (VT) of the particle position has been previously applied to analyze preferential concentration of inertial particles (Monchaux *et al.* 2010). However, we recently developed and applied a method of VT to compute the particle divergence and curl in a homogeneous isotropic turbulence (HIT) (Oujia *et al.* 2022). Here, we apply this method to a point-particle direct numerical simulation (PPDNS) data of four-way coupled particle-laden channel flow. In particular, we analyze the particle behavior in the viscous sublayer, the buffer layer, and in the log layer, their dependence on the particle mass loading and Stokes number.

Flow data and methods

The PPDNS data were obtained using the methods described in Esmaily *et al.* (2020). The particle two-way coupling force uses a correction for undisturbed fluid velocity, and collisions (inter-particle and wall) are computed with a hard sphere model. Flow cases spanning a range of mass loadings and Stokes numbers are described in Table 1. In all cases, the particles much heavier than the carrier fluid are present with a dilute volume fraction. Gravity is neglected. Each flow case was initialized randomly and run to reach steady state. 10 flow-through-times were used to time average Eulerian statistics. Lagrangian statistics are computed from 10 snapshots evenly distributed over the same time.

We apply the 3D modified VT of Oujia *et al.* (2022) to the particle positions. To compute the divergence of the particle velocity $\mathcal{D}(\boldsymbol{v}_p)$, we define n_p the local number density averaged over a cell as the inverse of the corresponding volume. As particles satisfy the conservation equation of the density, $D_t n_p = -n_p \nabla \cdot \boldsymbol{v}_p$ with D_t the Lagrangian derivative, using two time instants of the tessellation, we can determine the volume change. Similarly, the curl can also be expressed as the divergence of $\boldsymbol{v}$ projected onto the orthogonal plane of the direction of the curl through the origin and then rotated in a direction $\pi/2$. Further details of the computation of divergence and curl are available in Oujia *et al.* (2022).

	Re_τ	N_p	ϕ_0	St^+	α_p
Flow 1	225.1	1.426E+7	0.1	6.903	1.348E-5
Flow 2	226.9	5.704E+7	0.4	7.012	5.393E-5
Flow 3	233.8	1.426E+8	1.0	7.447	1.348E-4
Flow 4	273.1	4.509E+8	1.0	2.977	4.263E-4
Flow 5	262.9	1.426E+9	1.0	1.016	1.348E-3

Table 1: Parameters of the PPDNS data; the friction Reynolds number Re_τ, the number of particles N_p, the overall mass loading ϕ_0, the friction Stokes number St^+ and the particle volume fraction α_p.

Results and Discussion

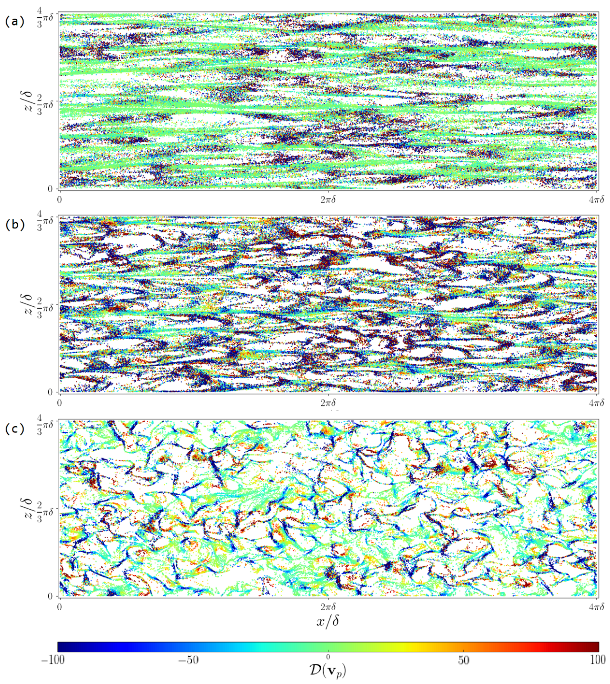

Figure 1: Spatial distribution of the particles colored with the divergence $\mathcal{D}_p$ for the three layers.

The spatial distribution of the particles colored with the divergence $\mathcal{D}_p$ for the viscous sublayer (a), the buffer layer (b), and the log layer (c) are shown in Figure 1 for Flow 1. In the viscous sublayer, particles are organized in long, low-speed streaks. The majority of particles, in green, have a near-zero divergence, indicating that the particles are transported without clustering. In the buffer layer, the streaks are less apparent, and some particles are organized into hairpin-like structures with spanwise curvature and non-zero divergence. These structures indicate that the particles have a stronger tendency to converge and diverge around the hairpins. Finally, in the log layer, the distribution of the particles is similar to that observed in HIT, with void regions and the particles organised in filament. Meanwhile, unlike HIT, the particles tend to have the same sign of divergence as their neighbors, meaning the particles are less likely to cross paths.

Figure 2 shows PDFs of the divergence for the three layers. In agreement with the observations of Figure 1, the variance

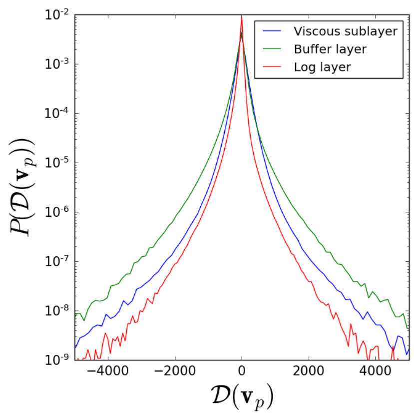

Figure 2: PDFs of the divergence the three layers.

is the largest in the buffer layer. This is expected because the near-wall peak in turbulent kinetic energy occurs at $y^+ \approx 12$. The buffer layer shows the greatest variance in divergence across all cases in Table 1. In all layers, the divergence distribution exhibits negative skewness, increasing in magnitude away from the wall, indicating a greater likelihood of intense clustering than divergence. We can also observe heavy tails, which is a sign of strong non-Gaussianity and the spatially intermittent behavior of the divergence, i.e. extreme events. The effect of mass loading, Stokes number and PDFs of the curl will be discussed in more detail in the presentation.

Conclusion

In this work, we applied the VT method to compute the divergence and curl of inertial particles in a four-way coupled particle-laden channel flow to gain insight into particle clustering in wall-bounded turbulence. Similarities to HIT are found in the logarithmic layer, and unique, active cluster dynamics are identified in the buffer layer. The divergence PDFs exhibit heavy tails which is a sign of extreme events.

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