MEASURING THE ORIENTATION AND ROTATION RATE OF 3D PRINTED PARTICLES IN TURBULENCE

Stefan Kramel[1], Guy G. Marcus[1], Shima Parsa[1], Brendan Cole[1], Rui Ni[1, 2]& Greg Voth[1]
[1]*Wesleyan University, Department of Physics, Connecticut, USA*
[2]*Yale University, Mechanical Engineering and Materials Science, New Haven, USA*

Abstract The orientation distribution and rotations of anisotropic particles in turbulent flows play a key role in many applications ranging from icy clouds to papermaking and drag reduction in pipe flow. However, experimental access to time-resolved orientations of anisotropic particles has not been easy to achieve. The use of 3D printing opens up the possibility to fabricate a wide range of particle shapes with smallest dimension down to 300 μm. So far, we have printed rods, crosses, jacks, triads, tetrads and helical particle shapes. We extract particle orientations from stereoscopic video images using a method of least squares optimization in Euler angle space. We find that in turbulence, the orientation and rotation-rate of many particles can be understood using a simple picture of alignment of both the vorticity and a long axis of the particle with the Lagrangian stretching direction of the flow.

Introduction

We introduce a new method to measure Lagrangian vorticity and the rotational dynamics of anisotropic particles in a turbulent fluid flow. Time-resolved measurements of the orientation and solid-body rotation-rate of particles are obtained from stereoscopic video images of their motion in a turbulent flow between oscillating grids with R_λ=91 (see figure 1). We have identified a class of particles that can be fabricated easily using 3D printing and whose orientation can be directly measured from the video images. So far, we have studied rods, crosses (two perpendicular rods) and jacks (three mutually perpendicular rods). For small enough particles, crosses rotate like disks and jacks rotate like spheres [1] so these particles allow measurements over the whole range of aspect ratios of axisymmetric ellipsoids.

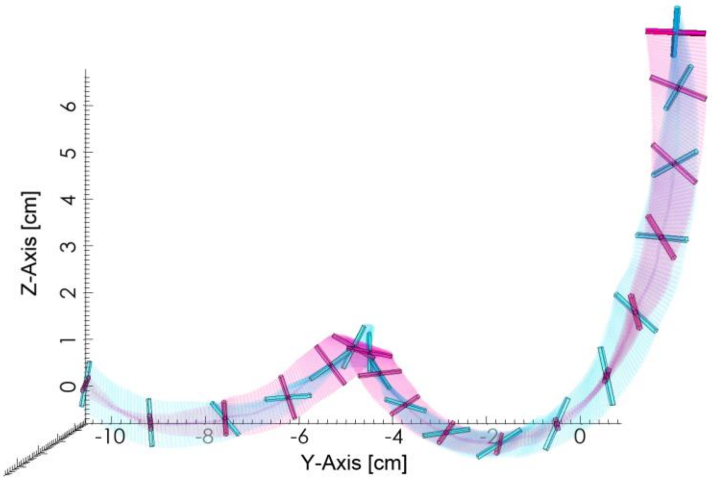

Figure 1. A reconstructed trajectory of a cross in three-dimensional turbulence. The length of the particle track is 336 frames, or 5.7 Kolmogorov time steps. A cross is shown every 15 frames. (Note: the crosses shown above are not drawn to scale so that the orientation can be clearly seen.)

Experiments and Results

Since a jack rotates just like a sphere, its solid-body rotation-rate couples only to the vorticity, making it a valuable instrument for direct Lagrangian vorticity measurements. Compared to other approaches [2, 3], our technique allows measurements of much smaller particles. We print jacks with a size of six Kolmogorov lengths, making them a good approximation to anisotropic tracer particles [4, 5].

Measurements of the alignment of crosses with the direction of their solid-body rotation-rate vector provide the first direct observation of the alignment of anisotropic particles by the velocity gradients of the flow. Our measurements show that crosses are preferentially aligned in turbulence with their symmetry axis $\boldsymbol{p}$ perpendicular to their solid-body rotation-rate vector $\boldsymbol{\omega}_s$. In figure 2, we plot the PDF of the magnitude of the cosine of the angle between those two quantities and compare them with numerical simulations. This alignment can be understood as a consequence of the particles aligning their long axis with the Lagrangian stretching direction of the flow defined by the eigenvector of the left Cauchy Green strain tensor corresponding to the maximum eigenvalue [6]. Since the vorticity also aligns with this eigenvector, particles preferentially rotate about their long axis which for a cross is perpendicular to ***p.***

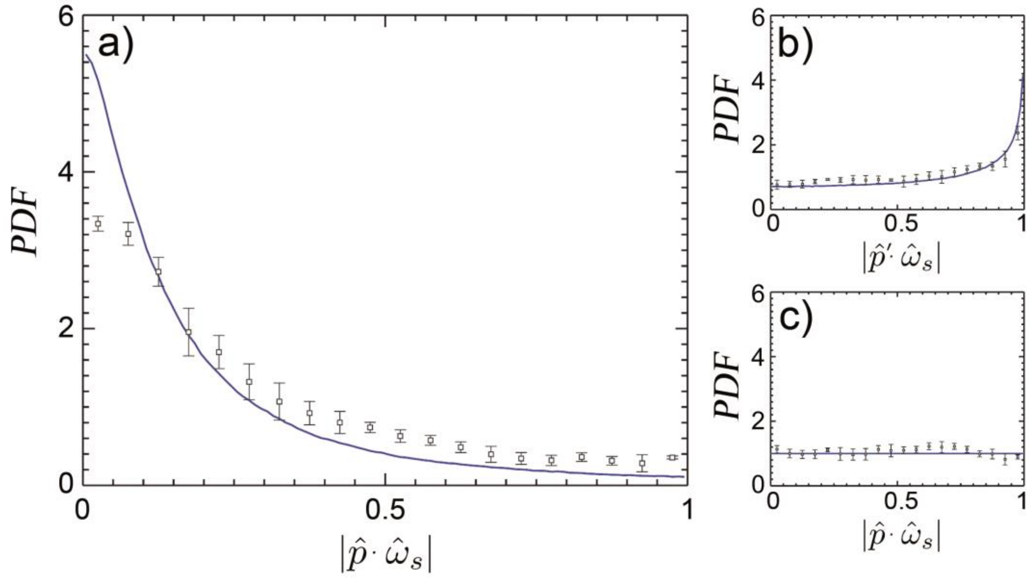

Figure 2. The PDF of the alignment between a particle's orientation ***p*** and its solid-body rotation-rate vector $\boldsymbol{\omega_s}$ for (a) crosses and (c) jacks. Symbols are experimental measurements and solid lines are numerical simulations. (b) shows the alignment of one of the arms ***p′*** of a cross with its solid-body rotation-rate vector.

Current Work

When a particle is larger than the smallest scale of turbulent motion its rotation provides a probe of the coarse-grained turbulent motion at the scale of the particle. Thus measurement of rotations of objects with different sizes provides a direct way to measure scale dependent dynamics. We have already observed inertial range scaling in measurements of the rotations of long rods [5], but theoretical analysis of the rotations of rods is complicated because the rods preferentially align with the vorticity, and this strongly affects their rotation rate [6, 7]. We propose a simpler approach to observe the inertial range scaling of particles that rotate like spheres by tracking the rotations of four armed particles with tetrahedral symmetry. Moving to 4 armed "tetrads" with higher aspect ratio allows a significant improvement in orientation measurement accuracy over our previous measurements of jacks because of decreased shadowing of one arm by another. This approach enables us to reveal the physics of the turbulent cascade from a very different perspective, namely the rotations of rigid particles.

We have also identified an interesting class of helical particles that show preferential rotation in turbulent flows. The ability to use 3D printers to rapidly fabricate a wide range of particle geometries offers a powerful new tool for studying complex particles in turbulent flows.

References

[1] G. G. Marcus, S. Parsa, S. Kramel, R. Ni and G. A. Voth. Measurements of the solid-body rotation of anisotropic particles in 3d turbulence. *New Journal of Physics* 16 (10), 102001, 2014.

[2] R. Zimmerman, Y. Gasteuil, M. Bourgoin, R. Volk, A. Pumir and J.-F. Pinton. Tracking the dynamics of translation and absolute orientation of a sphere in a turbulent flow. *Review of Scientific Instruments*, 82(3):033906, 2011.

[3] S. Klein, M. Gibert, A. Bérut and E. Bodenschatz. Simultaneous 3d measurement of the translation and rotation of finite-size particles and the flow field in a fully developed turbulent water flow. *Measurement Science and Technology*, 24(2):024006, 2013.

[4] M. Shin and D. L. Koch. Rotational and translational dispersion of fibres in isotropic turbulent flows. *Journal of Fluid Mechanics,* 540:143-173, 2005.

[5] S. Parsa and G. A. Voth. Inertial range scaling in rotations of long rods in turbulence. *Physical Review Letters,* 112:024501, 2014.

[6] R. Ni, S. Kramel, N. T. Ouellette and G. A. Voth. Measurements of the coupling between the tumbling of rods and the velocity gradient tensor in turbulence. *Accepted for publication in Journal of Fluid Mechanics*, 2014.

[7] K. Gustavsson, J. Einarsson and B. Mehlig. Tumbling of small axisymmetric particles in random and turbulent flows. *Physical Review Letters*, 112:014501, 2014.