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# Measurement of particle and bubble accelerations in turbulence

R. Volk<sup>(1)</sup>, N. Mordant<sup>(2)</sup>, G. Verhille<sup>(1)</sup> and J.-F. Pinton<sup>(1)</sup>

<sup>1</sup> *Laboratoire de Physique, de l'École normale supérieure de Lyon,  
CNRS UMR5672, 46 Allée d'Italie, 69007 Lyon, France*

<sup>2</sup> *Laboratoire de Physique Statistique de l'École normale supérieure de Paris,  
CNRS UMR8550, 24 rue Lhomond, 75005 Paris, France*

We use an extended laser Doppler technique to track optically the velocity of individual particles in a high Reynolds number turbulent flow. The particle sizes are of the order of the Kolmogorov scale and the time resolution, 30 microseconds, resolves the fastest scales of the fluid motion. Particles are tracked for mean durations of the order of 10 Kolmogorov time scales. The fastest scales of the particle motion are resolved and the particle acceleration is measured. For neutrally buoyant particles, our measurement matches the performance of the silicon strip detector technique introduced at Cornell University [2, 3]. This reference dynamics is then compared to that of slightly heavier solid particles (density 1.4) and to air bubbles. We observe that the acceleration variance strongly depends on the particle density: bubbles experience higher accelerations than fluid particles, while heavier particles have lower accelerations. We find that the probability distribution functions of accelerations normalized to the variance are very close although the air bubbles have a much faster dynamics.

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The Lagrangian approach to fluid dynamics is a natural one when one addresses problems related to mixing and transport [1]. It has also been widely studied in the context of intermittency in fully developed turbulence. In recent years, several novel experimental techniques have been developed. The pioneering optical tracking method developed in the Cornell group has revealed that fluid particles experience extremely intense accelerations, with probability density functions (PDFs) having stretched exponential tails [2, 3]. Initially limited to very short particle tracks, the technique has been extended with the use of ultrafast optical cameras [4], and is currently applied to the study of multiple particle statistics [5]. Individual particles have been tracked for time duration of the order of the flow integral time scale using an acoustic technique [6]: in an insonified volume, individual particles scatter a sound wave whose Doppler shift carries the tracer velocity. In reason of the very fast decrease of the acoustic scattering cross-section, this method is limited to particles with size of the order of the wavelength, *i.e.* inertial ranges sizes [7] when using acoustics. However the principle of the technique is completely analogous to laser Doppler velocimetry (LDV), provided that expanded light beams are used. Interference fringes are created at the intersection of two wide laser beams; a particle that crosses these fringes scatters light with a modulation frequency proportional to its velocity component perpendicular to the direction of the fringes [8]. The advantage, compared to the acoustic method, is that the much smaller wavelength allows a better resolution in space and also the use of smaller tracer particles.

In this Letter, we describe the principles of this technique and validate it against the known features of the Lagrangian acceleration statistics in a fully turbulent von Kármán flow at  $R_\lambda \leq 850$ . We then apply it to

track the dynamics of particles whose density differs from that of the fluid. The dynamics of such *inertial* particles is relevant for many engineering applications related to transport, mixing, dispersion, etc [9]. Significant theoretical and numerical progress in this domain has been made in the limiting case of infinitely heavy, pointwise particles [11] and has received experimental verifications [12, 13]. We report the first experimental measurements of accelerations of particles having a density in the range  $10^{-3}$  (air bubbles) to 1.4 (PMMA) in the same highly turbulent flow. Taking into account the added mass effect for small spherical particles (*i.e.* the displacement of fluid elements by the particle motion), the effective density of the bubbles is only 3 times less than that of the fluid, while the PMMA particles are roughly 1.5 times larger. Because of the mismatch of density, light particle tend to be trapped in high vortical regions: as result of a lower inertia, the centrifugal force can not compensate the pressure gradient which drive them into the core of the vortices. On the contrary the centrifugal force is stronger than the pressure gradient for heavy particles so that they are ejected from vortex cores and concentrate in high strain regions [14]. Because of this distinct spatial sampling of the flow, particle with different buoyancy are expected to exhibit quite different dynamical behavior. Indeed, we do find that the particles have different dynamical characteristics such as acceleration variance or correlation time. The PDFs of their accelerations remain close for value less than about 10 times the acceleration variance, and differ for higher values.

The Laser Doppler technique is based on the same principle as the ultrasound Doppler method which was shown to be very valuable for Lagrangian particle tracking [6]. In order to access dissipative scales, and in particular for ac-