The pirouette effect in the chaos of turbulence

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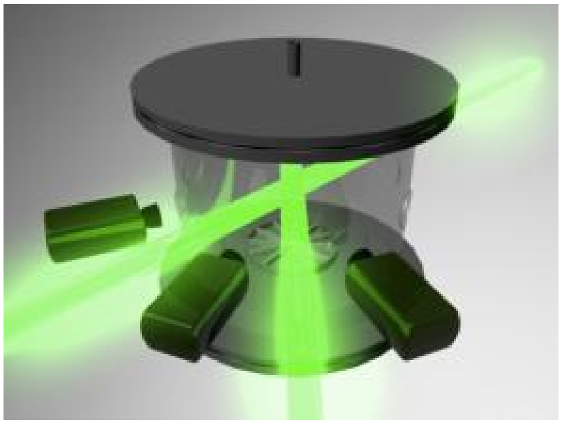

Sight set on turbulences: Physicists of the Max Planck Institute for Dynamics and Self-Organization used several cameras to observe particles which are whirled around in a turbulent water flow and illuminated by a very bright laser. Analysing the motion of four particles, the researchers could observe that the local alignment of turbulent rotation conserves angular momentum, similar to an ice-skater performing a pirouette. Credit: Eberhard Bodenschatz/Max Planck Institute for Dynamics and Self-Organization

(PhysOrg.com) -- The quick mixing of coffee and milk after stirring or the formation of raindrops in clouds: these are just two of many phenomena in which turbulent flows play a decisive role. Researchers at the Max Planck Institute for Dynamics and Self-Organization and the Ecole Normale Superieure de Lyon have now discovered that the seemingly random turbulent flows actually have an astonishingly uniform structure. According to the findings, vortices are a basic ingredient of turbulent flows and they behave similarly to an ice-skater performing a pirouette – a technique whereby the skater bends his or her arms to increase the speed of rotation. The researchers monitored this pirouette effect in vortices of various sizes in a turbulent liquid. In doing so, they unravelled a mystery that has confounded turbulence researchers for decades – namely the question of how energy flows from large to ever-smaller vortices, and how it is ultimately converted to heat in the smallest vortices.

As far back as the first half of the last century, physicists were already exploring the question of how turbulent flows convert the energy of a directional flow into omni-directional heat energy. The explanation they came up with was the so-called “energy cascade” concept – a concept according to which the kinetic energy, e.g. of a river, initially flows in large, rapidly rotating vortices when cascading down a waterfall. The large vortices then break down into smaller vortices, which in turn break down into even smaller ones. The smaller the vortices become, the slower the speed of their rotation. In the slowly rotating mini-vortices, the strength of the friction is such that the kinetic energy is ultimately converted into heat energy.

This energy cascade process is used by people on a daily basis, for example in mixing processes: when stirring milk in coffee, the milk flow initially triggered by the spoon is converted within seconds to a directionless, even distribution of tiny milk drops. The base materials of chemical reactions are also mixed with the aid of turbulent flows, the process thereby being much faster than if the materials are not mixed.

Turbulent flows from the perspective of floating particles

However, researchers do not yet understand the mechanisms of turbulent flows. Such an understanding could greatly simplify computer modelling of turbulent processes and thus, for example, the simulation of clouds in climate models. Physicists Eberhard Bodenschatz and Haitao Xu from the Max Planck Institute for Dynamics and Self-Organization in Göttingen and Alain Pumir from the Ecole Normale Superieure de Lyon have now taken an important step towards understanding turbulent flows. By studying a single floating particle in a turbulent flow for the first time, they discovered a basic ingredient in turbulent flows.

To this end, they used a high-speed camera to monitor polystyrene particles in a turbulent water flow, which were illuminated by a very bright laser. When analysing the images, they singled out a particle surrounded by three further particles. These particles were separated by an equal distance so that they formed a tetrahedron. They observed how the positions of the particles with respect to one another changed over time, namely how the tetrahedron in the turbulent liquid changes shape and how it rotates. This process involved extreme time-lapse recordings of 30,000 images per second.

The result astonished the physicists: the particles effectively performed a dance similar to the pirouette in ice-skating. When an ice-skater bends his or her arms while spinning, the speed of the rotation drastically increases. The reason for this is the conservation of a physical variable known as the angular momentum. A particle of mass located outside the axis of rotation exerts greater resistance to the rotation than a particle of mass located within the axis, which means that the speed of the rotation increases as the particle of mass moves inwards.

The simulation of turbulent flows is now becoming easier

Bodenschatz and his team observed an analogous effect in turbulent water. The flow stretched the tetrahedron so that it became thinner. In addition, the tetrahedron's axis of rotation aligned so that it was parallel to the original stretching direction of the flow. The stretched tetrahedron's speed of rotation ultimately increased. "All the while, the angular momentum was conserved," says Bodenschatz. In this way, the observed dynamics correspond with a pirouette of a spinning ice-skater. Bodenschatz and his colleagues thus refer to this as the "pirouette effect".

The fact that the angular momentum of the vortex is conserved in the centre of a turbulent liquid was something that surprised the physicists. "We do not yet understand why this is the case," says Bodenschatz. The vortices in the chaos of a turbulent flow should actually experience torsional forces that change their angular momentum. The pirouette effect shows that "a relatively high degree of order" prevails within the chaos of a turbulent flow, says the physicist.

This order in chaos can be seen on different size scales. Using the method outlined above, the Göttingen-based physicists studied vortices with diameters ranging from a few millimetres to several centimetres. "All demonstrated the pirouette effect," says Bodenschatz. "Our result confirms the energy cascade model," says the physicist. Since the 1930s, researchers have acted under the assumption that the energy cascade was heavily influenced by vortex dynamics. According to this concept, the vortices in the flow stretch and rotate faster around their longitudinal axis – thus becoming instable and breaking down into smaller vortices, which then undergo the same process until a cascade is reached with very small vortices.

In the last thirty years or so, however, this notion appeared to be refuted by calculations according to which the axis of rotation never aligns with the strongest stretching direction of the flow, but rather remains vertical to this. “These calculations, however, only examined snap shots of the flow field”, says Bodenschatz. They represent, so to speak, snapshots. “For the first time, on the other hand, we monitored how vortices float with the liquid,” says the physicist. This is the only way to trace the development of a vortex over time. An analysis of a single floating particle in the flow has now confirmed the pirouette effect, something that has only been an assumption up until now.

Bodenschatz sees this result as a step towards solving an important problem in the computer-based simulation of turbulent flows. “Many aspects of turbulent flows can already be simulated, but we have not yet been able to simulate how different size scales interact with one another.” He believes that this could change if we have a better understanding of the dynamics of vortices of different sizes.

More information: Haitao Xu, et al. The pirouette effect in turbulent flows, *Nature Physics*, 5 June 2011; DOI: 10.1038/NPHYS2010

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