Maths, Physics & Chemistry

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Creating the world's fastest rotating object

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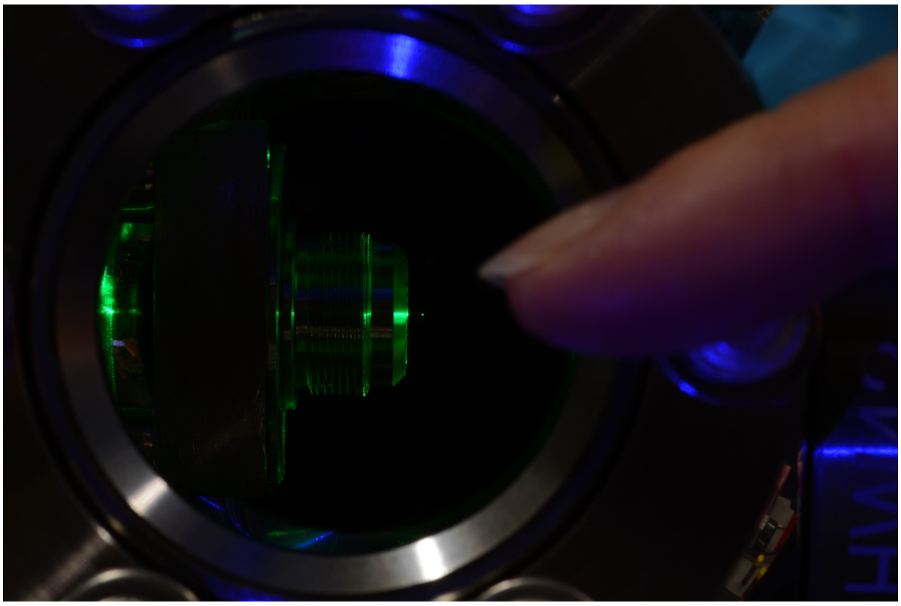
ABSTRACT

The blades in the turbine of a fighter jet aircraft can spin nearly one thousand times each second, but spinning any faster makes them explode. What is the highest rotation rate at which a mechanical object can revolve?



Photograph of a levitated particle. The particle is made visible by green laser light illumination. A finger, pointing at the particle, illustrates the size of the experiment. Image credits: R. Diehl and R. Reimann

Fighter jet aircrafts need to be fast. It therefore appears intuitive to make their turbines spin at the highest rotation rates possible. Following this approach, one will encounter an unpleasant surprise. At rotation rates around 1000 revolutions per second, the turbine blades start to disintegrate, and the whole turbine explodes. There, the maximum circumferential speed, i.e. the speed of the tip of a blade, is about 1000 m/s. In contrast, the speed in the center of the turbine, is zero. This huge difference in speeds leads to an enormous stress in the material, which eventually results in the described explosion. The maximum circumferential speed of 1000 m/s seems to be a quite general material limit. In the same way as turbines, 0.5 mm steel balls explode if they rotate more than 700,000 times a second, which corresponds to a circumferential speed of about 1000 m/s.

Since the circumferential speed decreases with the size of the rotating object, the world's fastest rotating object needs to be minuscule, and it cannot be attached to a normal motor to drive its rotation, because the motor itself would explode, too. So in order to create the world's fastest rotating object we must leave the realm of things that we can easily see by eye, and enter the world of objects that are a thousand times smaller than the diameter of a hair... the nanoworld. In this world we find particles so tiny that they can even be levitated and manipulated purely by light (see picture). We decided to spin these tiny particles, very, very fast.

The particles we are using for our experiments are made from fused silica and have a diameter of 100 nm. We trap one of those nanoparticles in a strongly focused laser beam which functions as an optical tweezer. The optical tweezer does not only levitate the nanoparticle but can also be used as the motor to drive the particle into rotation. To turn this motor on, we set the polarization of the laser beam to circular. The polarization describes how the electric field of the light evolves through time at a certain position. In the circular polarization state the electrical field of the laser rapidly revolves in a circle, making the particle rotate. To achieve the highest rotation rates, we had to mitigate the friction from molecules in the air, which bump into our rotating particle, hindering its rotation. To do this, we placed our now optically trapped and optically driven particle inside a vacuum chamber. Because a vacuum chamber is almost completely devoid of air, our particle was able to spin freely, with about 100 million less “bumps” from air molecules than before. Inside the vaccum chamber, and spinning our particle with an optical power of about 200 mW (corresponding to about 100 standard laser pointers) we measured it doing one billion revolutions per second, making it the world’s fastest rotating object. In very recent and unpublished measurements we recorded even rotation rates exceeding a circumferential speed of 1000 m/s!

Indeed, a rapidly rotating nanoparticle is a promising testbed for fundamental material stress tests. Material test particles can be manufactured at the nanoscale without defects and therefore can be useful to explore fundamental material stress limits. In contrast, a macroscopic probe (e.g. a turbine blade or a mm sized steel ball) cannot easily be manufactured without defects and would break due to a crack or a scratch and not due to atomic bonds of the material being ripped apart. Furthermore, it is possible that materials on the nanoscale behave differently than on the macroscale, so studying the rotation rate at which our tiny particles explode would bring new insights to material science.

On the other hand, our experiments might prove useful to teach us about fascinating fundamental physical principles. Quantum mechanical effects begin to show up at the nanoscale. If we were able to perfectly isolate our experiment from all kinds of possible friction forces (air molecules, electric fields,…), there would still be a force that breaks the rotation of the maximally freely rotating particle. This force arises from quantum fluctuations of the vacuum. In other words, the fluctuations of what one could call ‘nothing’ would break the rotation of the particle. Even though such a quantum experiment is very challenging to perform, it is a fascinating perspective for our tiny rotors, and something we would love to do...soon!