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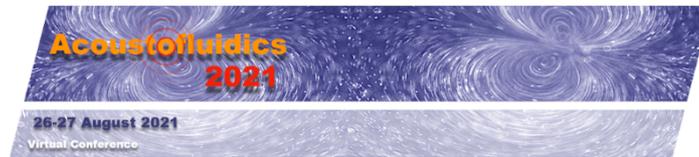
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# Study of the Rayleigh limit by Acoustic Force in Microgravity

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## Introduction

In a Bulk Acoustic Wave (BAW) resonator, spherical objects, such as particles, can be maintained in an equilibrium position, between the walls of the resonant cavity. In the so-called acoustic levitation plane the gravity is counterbalanced by the Acoustic Radiation Force (ARF) created when the resonance condition is respected (height of the cavity  $h$  equal to the half of the acoustic wavelength  $\lambda_{ac}$ ). The analytical expression commonly used to describe the ARF applied to a spherical particle is obtained by assuming that the acoustic wavelength is large compared to the diameter of the irradiated particle, an assumption called "Rayleigh's approximation" or Rayleigh's limit [1,2]. It is therefore perfectly applicable to objects of microscopic sizes ( $d_p = 1$  to  $20 \mu m$ ) and an ultrasonic source of the order of a few MHz ( $\lambda_{ac}$  of the order of a few hundred  $\mu m$ ). In this context, particles or cells can be moved toward the acoustic levitation plane where they can form large aggregates.

It was shown recently that it is possible to maintain in acoustic levitation large objects (cells spheroids) whose diameter is close to the acoustic wavelength [3], in contradiction with the Rayleigh's hypothesis. In order to study more precisely the limits of this hypothesis it is interesting to run experiments in microgravity. In this case, the gravity will not limit the ARF and it will be possible to handle large and / or dense objects, which would sediment quickly in standard laboratory conditions on Earth. We present in this talk the first experimental results showing that indeed ARF can move and levitate large objects far beyond the Rayleigh's limit.

## Theoretical background

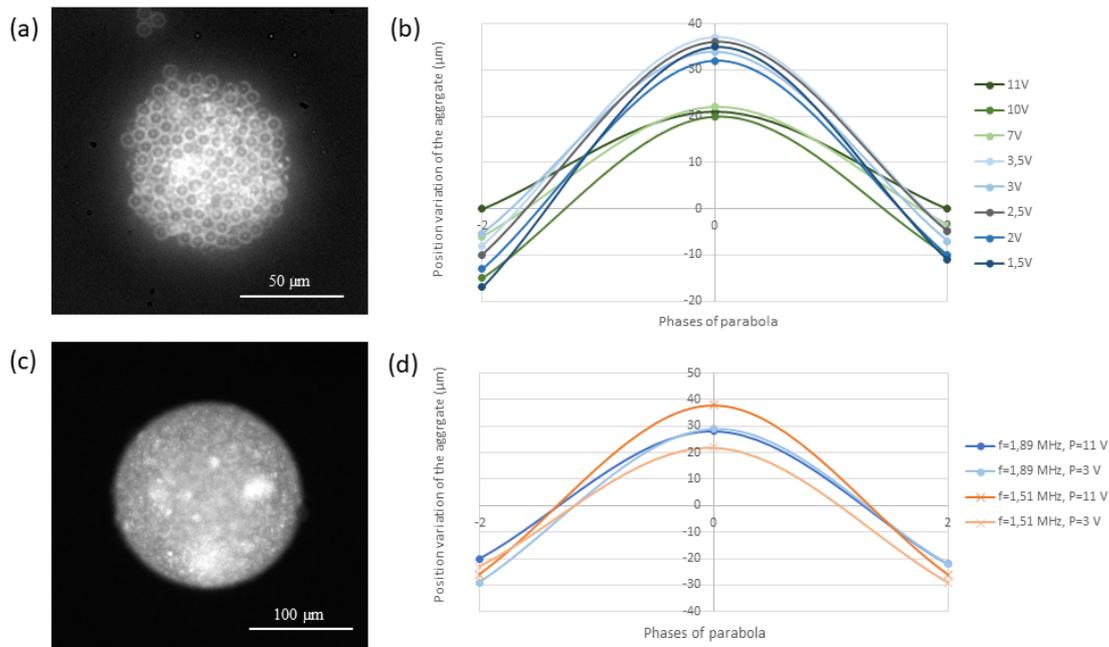
As previously described [4], the ARF can be considered as "artificial gravity" in a Zero-G environment allowing the self-assembly of a large number of microparticles which would have stayed in suspension otherwise. When levitating a large number of cells, we can form aggregates as large as the acoustic wavelength, meaning we overcome the Rayleigh limit. Indeed, being able to levitate large objects ( $500 \mu m$  diameter vs  $\lambda_{ac} = 700 \mu m$ ) shows that either the ARF expression is still valid or that it should be corrected for large objects. Numerical simulations were developed to extract the trajectories of several acoustically and hydrodynamically interacting particles beyond the Rayleigh regime to replicate experimental results obtained with large concentration of particles clumping at pressure nodes [5]. However, to our knowledge, this phenomenon was never investigated experimentally, especially in the context of microgravity.

Therefore, to shed light on this peculiar behavior, we chose to study, during the parabolic flight campaign of Novespace in March 2021, large and dense particles in microgravity which could not be moved by the ARF on Earth.

## Experiment design for microgravity

In our conventional lab set-up, the acoustic levitation is studied in home-made sub-millimetric cavities. We observe aggregates with an inversed microscope and a camera. The ARF is generated by an ultrasonic transducer powered by a sinusoidal electric signal and controlled by a computer. The working frequencies we uses are around 2 MHz so that the ultrasound can resonate in our home-made cavities. The generator can provide an electrical power between 1 and 12V allowing to modulate the acoustic energy inside the chamber and thus the ARF.

To run these experiments in the Airbus Zero-G of Novespace, we designed two racks. The monitoring rack was conceived to allow for quick data acquisition while the experimental setup was designed to fit into a sealed Zarges box for security reasons. The particles in acoustic levitation were studied using an inverted Zeiss microscope and a PCO Panda Bi camera. A piezoelectric stage from ASI imaging was used in order to follow closely the beads during the parabolas and extract their precise position. The variety of samples were composed of polystyrene beads of 1.00 g/cc and 5  $\mu m$  in diameter, polyethylene fluorescent beads with a density of 1.00 g/cc and sizes ranging from 150 to 700  $\mu m$  as well as Titanium beads with a density of 4,5 g/cc and 150  $\mu m$  in diameter.



**Figure 2:** (a) Picture of the aggregate of small polystyrene beads (5  $\mu\text{m}$  in diameter) and (b) its position variation during the parabola phases. Each lines represents a different experiment and thus a different parabola. The parameter which varied between experiments was the acoustic power delivered. The low and high regimes are shown in blue and green shades respectively. (c) Picture of the big fluorescent bead (150  $\mu\text{m}$  in diameter) and (d) its position variation during the parabola phases. The low and high regime are defined as light and dark color respectively and the two different resonant frequencies are represented by orange shades and crosses for 1.51 MHz and blue shades and dots for 1.89 MHz.

## Results

We first created an aggregate of small beads (Fig 2.a) to measure the evolution of the position of the acoustic levitation plane for different gravities phases during one parabola, starting with a 2g phase followed by a microgravity period of about 20 s and ending with another 2g phase. The position of reference was taken at standard gravity conditions (1g), before the parabola. All values are then variations compared to the 1g case. In all case, we use a 2,04 MHz source which is the resonant frequency of our cavity. In Fig 2.b., the position variation of the aggregate is plotted against the different phases of the parabola. We first distinguish two regimes at low ( $P = [1.5 ; 3,5]$  V) and high ( $P = [7 ; 11]$  V) power. At high power, the levitation plane position varied less than at low power. In particular, the aggregate position during the microgravity phase was almost two times higher at low power compared to high power.

We then studied bigger particles under those two regimes and at different resonant frequencies. As expected, the highest relative position of the bead in microgravity was at the lowest frequency (1.51 MHz). However, it is relevant to notice that the position variation at low regime in microgravity was two times smaller than at high regime and even smaller than for the higher frequency at the same acoustic power. These results contradict the results obtained with the aggregate of small beads. This could be explained by the cohesive forces between particles playing a role in the way particles in the aggregate respond to ARF compared to an independent large particle. We were not able to levitate bigger polyethylene beads (diameter > 500  $\mu\text{m}$ ) but the dense Titanium beads showed a response when submitted to ARF and even formed plane aggregates.

## Conclusion

Thanks to experiments in parabolic flights we were able to handle large and dense particles that could not be moved in standard gravity conditions. We carried out parametric studies and demonstrated that it is indeed possible to handle large particles or large aggregates of particles using ARF beyond the Rayleigh limit.

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