# MAGNETIC LEVITATION OF WEAKLY CONDUCTING LIQUID DROPLETS

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**Abstract:** High DC magnetic field levitation for a noncontact liquid material properties measurements are investigated in detail using the numerical modeling techniques and comparing to the experimental observations of levitated water droplets, NaCl solution and ethanol. The shapes of droplets are compared using high frequency video recording and the corresponding numerically generated free surface images following the time evolution. By adding even a weak electrical conductivity to the liquid properties, the surface waves are damped considerably in the presence of the high magnetic field.

## 1. Introduction

High DC magnetic field levitation, using para- and dia-magnetic properties of the materials, can be used for advanced material research without the drawbacks related to the intense recirculating turbulent flow vortices appearing when the AC magnetic field is used for levitation. In practice a small vibration of the droplet center of mass position remains even in carefully conducted experiments [1]. Frequency measurements using the oscillating drop technique have been conducted for small size water droplets by Beaugnon et al. [2], and more recently by Hill & Eaves [1], in which a derivation of the frequency modifications due to the magnetic field are made and compared with the experimental results. The experimental results are replicated with the numerical simulations [3] accounting for the dynamic free surface change, internal flow and the centre of mass motion within the magnetic field from a magnet model. By adding an electrical conductivity to the liquid properties in the presence of the high magnetic field, the surface waves are either damped or their oscillation frequencies are shifted relative to the Rayleigh self-oscillation modes [4]. The numerical predictions for larger size liquid droplets show that the droplet centre of mass continues the oscillating motion without a significant damping [3]. This means that the magneto-gravitational potential, which for a static levitation would be constant along the droplet surface, experiences a similar oscillation as the free surface is moving across the potential isolines. The effect is more important for large size liquid droplets due to interaction of the surface wave modes and the magnetic force modulation.

These two effects are investigated in detail using the numerical modeling techniques and comparing to the experimental observations of levitated water droplets, NaCl solution and ethanol. The shapes of droplets are compared using high frequency video recording and the corresponding numerically generated images following the time evolution of the free surface.

## 2. Experimental procedures

The experiments were conducted at the Grenoble ‘Laboratoire National des Champs Magnétiques Intenses’ (LNCMI) on the vertical large bore magnet capable to reach 24 T in the centre position. The diamagnetic levitation is possible at the upper part of the magnet where the negative gradient of the magnetic field counteracts the gravitational force on the diamagnetic material droplet. The schematic view of the magnet, as generated from the numerical model used in this paper, is shown in the Figure 1. The magnet consists of several coil blocks carrying specially adjusted currents to ensure the required distribution of the magnetic field along the axis (the measured values are shown in the Figure 1). The computed

result, using the finite current element discretization and the Biot-Savart law, is shown for comparison in the same Figure 1.
A syringe connected via a plastic tube to a needle is used to inject a measured amount of diamagnetic liquid in the levitating zone of the magnet after the careful adjustment of the magnetic field intensity in order to obtain the magnetic 'trap' conditions. These adjustments need to be corrected for different material liquids and sizes of the levitated droplets. The experimental observations of levitated desalinated water, sodium chloride (NaCl) 20% water solution and pure ethanol droplets. The shapes of droplets are compared using high frequency video recordings from two cameras: at the side and top position of the droplet.

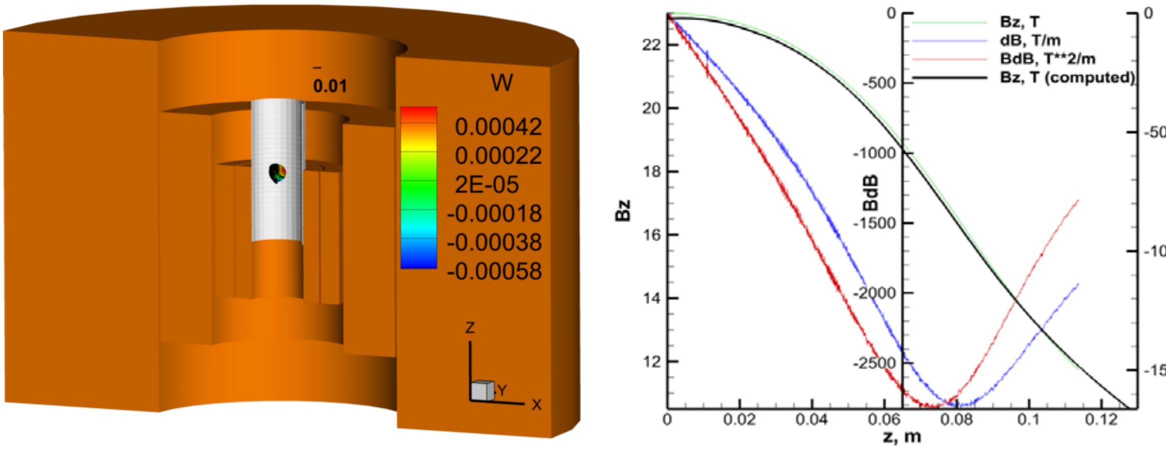


Figure 1: LNCMI (Grenoble) magnet numerical model representation used for DC magnetic levitation and the magnetic field measured and computed properties along the central axis.

## 3. The mathematical model and results

The mathematical basis of the present model is the time-dependent Navier-Stokes and continuity equations for an incompressible fluid [3]. The numerical solution of the problem is obtained using the pseudo-spectral collocation method, employing the continuous co-ordinate transformation for the shape tracking. The time-dependent fluid flow problem is set with appropriate boundary conditions: at the free surface of the liquid the normal hydrodynamic stress is compensated by the surface tension. The free surface position moves as determined by the force balance and the kinematic conditions.
The EM effects are computed at each new time step using the finite current element discretization and the Biot-Savart law. This means that the magneto-gravitational potential on the surface $U(R_s)$, defined by

$$\nabla(\rho g z - \chi_v |B|^2 / (2\mu_0)) = \nabla U \,, \tag{1}$$

experiences similar oscillation as the free surface is moving across the potential isolines. The effect is more important for large size liquid droplets leading to interaction of the surface wave modes and the magnetic force modulation. The position of the potential minimum determines the location of the magnetic 'trap' as seen in the Figure 2 for the stable and unstable levitation.

The numerical simulation was initiated by positioning the droplet in the stable magnetic potential minimum and perturbing the surface using the first 7 normal mode superposition of a small amplitude $0.01R_0$, where $R_0$ is the unperturbed spherical radius. The total perturbation is adjusted by the mode n=0 to preserve the volume of the initial sphere and to comply with the analytical Rayleigh normal mode frequencies (as will be shown in the Figure 6). The animated views of the computed droplet oscillations closely resemble those observed in the experiment, as can be seen from the instantaneous views in the Figures 3 and 4. The levitated ethanol droplet of 2 cm in diameter gives the most stable oscillations. The water droplet often is subject to relatively wild response to small perturbations, particularly when increasing the size to 3 cm.

When the salt solution was levitated, it was quite evident that the overall stability of the weakly electrically conducting droplet is improved, giving more smooth response to perturbations and a faster damping. This was particularly evident for the larger 3 cm size droplets. Figure 5 shows the computed oscillations of the free surface $R_t$ at the top position of the droplet. The red dotted line shows the 7 normal mode only oscillation in the absence of the magnetic field. The solid line represents the water droplet oscillation in the 16.5 T field (in the magnet centre), which at the levitation position is about 11 -13 T variable field intensity. The dash-dotted line represents the 20% salt solution droplet oscillation. The damping effct of the electrical conductivity is particularly well seen from the graph on the right of the Figure 5, where the centre of mass $Z_c(t)$ position is deducted from the surface position $R_t(t)$ giving the surface wave only presentation.

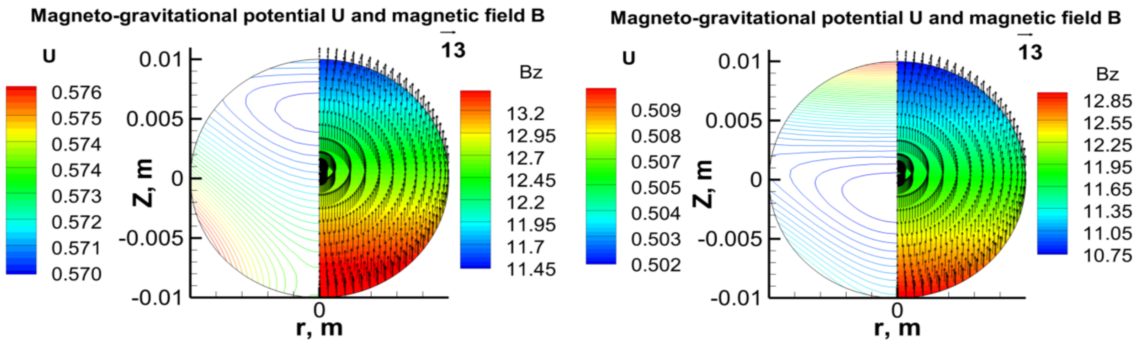


Figure 2: Computed magneto-gravitational potential and the magnetic field in the 2 cm diameter water droplet at t = 0: (left) unstable position at z = 0.072 m above the magnet centre, (right) stable position at z = 0.079 m.

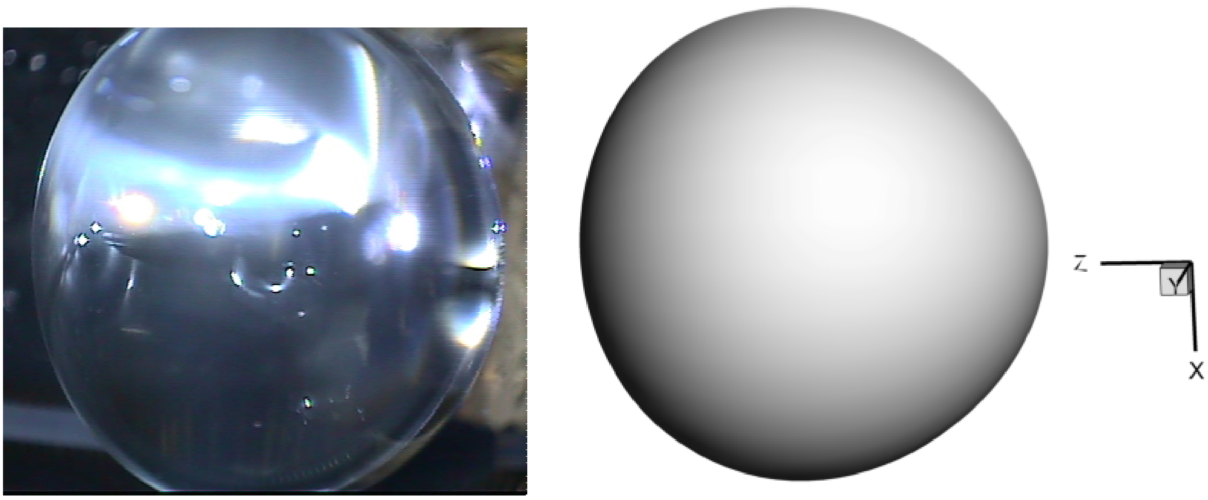


Figure 3: Images of the ethanol droplet D = 2 cm in the bore of experimental magnet and the numerically simulated (note that the vertical direction is horizontal in order to match the view from the side camera).

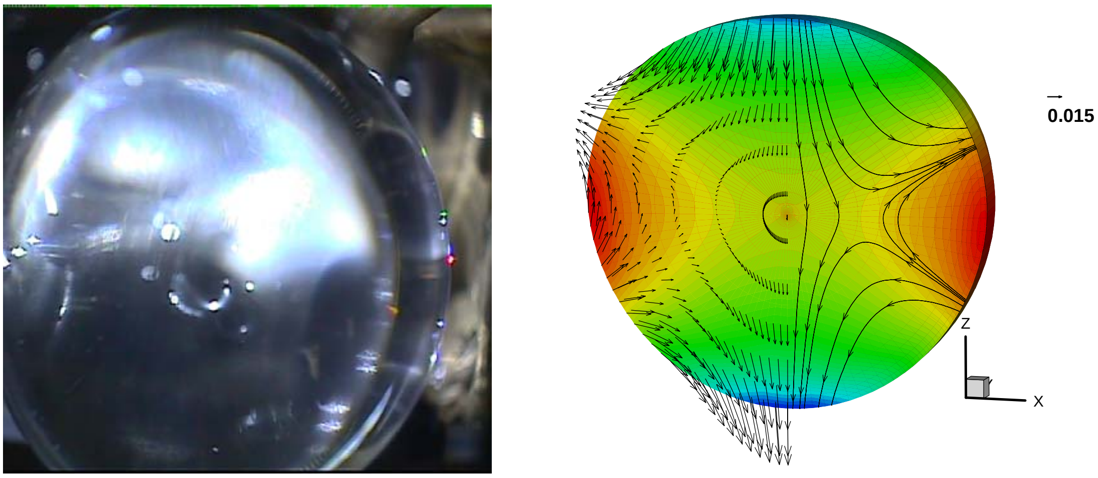


Figure 4: Images of 2 cm salt water droplet in the bore of experimental magnet at 16.1 T in the magnet centre and the numerically simulated at 16.5 T (accounting for 0.3 T air magnetic buoyancy correction).

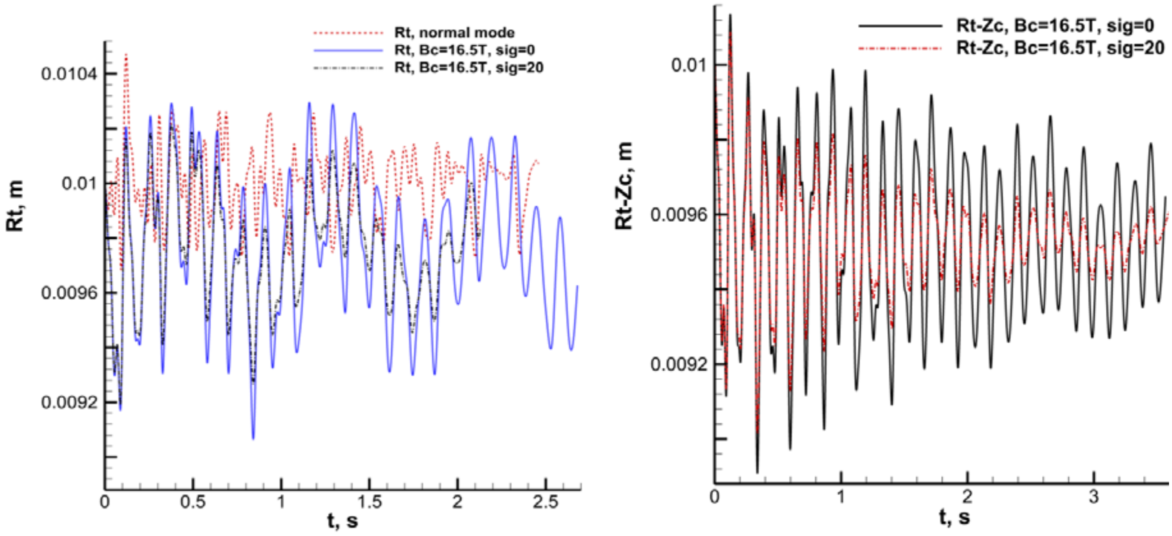


Figure 5: Computed oscillations of 2 cm water and salt water droplets in the bore of magnet at 16.5 T: a combination of 7 initial Rayleigh modes (dotted line), water with electrical conductivity 0, and the salt water conductivity 20 (1/Ωm).

The computed power spectra (Figure 6) provide the quantitative evidence for the frequency shift to slightly larger values as observed in the previous experiments [1,2]. It is encouraging to see that the additional property of the electrical conductivity of the salt water does not shift the frequency for the smaller droplets (2 cm). However the frequency shift is increased for the larger 3 cm droplet (see the Figure 6, right) because of the increased nonlinearity of the surface wave interaction, which is a well known phenomena even for the pure normal mode oscillations.

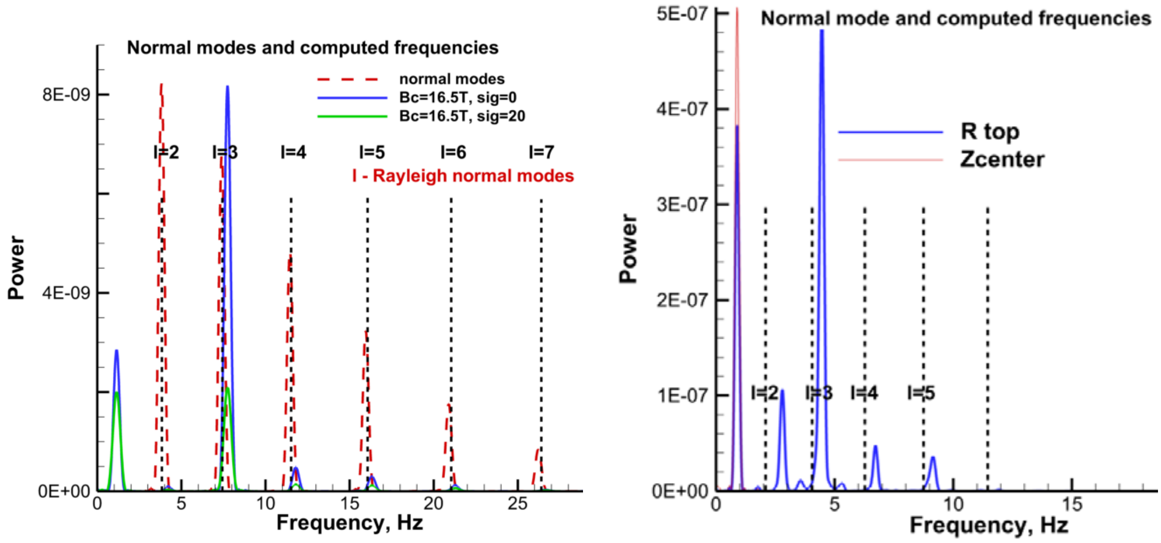


Figure 6: (Left) computed oscillation frequencies (power spectra) for the 2 cm water and salt water droplets in the bore of magnet at 16.5 T, and (right) - the 3 cm salt water droplet spectra at 16.7 T.

## 5. Conclusions

It is experimentally and numerically demonstrated that even a weak electrical conductivity has a significant effect to stabilize the magnetically levitated droplets using their diamagnetic properties. The damping effect is due to the low density induced electrical currents and does not affect the oscillation frequencies required to determine the surface tension material property. The presence of a weak electrical conductivity permits to levitate larger volumes of liquid in relatively more stable conditions.

## 6. References

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