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# Droplet oscillations driven by an electric field

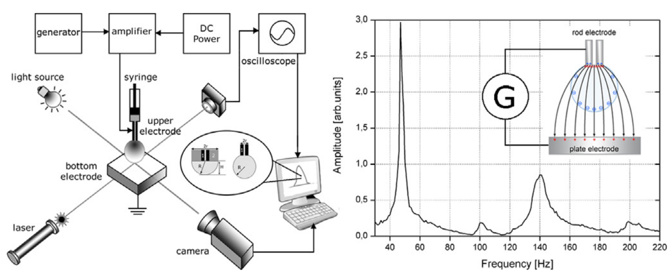
Nikolay Zografov*, Nikolay Tankovsky, Andreana Andreeva

*University of Sofia, Faculty of Physics, 5 James Bourchier Boulevard, Sofia 1164, Bulgaria*

## HIGHLIGHTS

- Electrically driven oscillations of a spherical and hemispherical droplet.
- Resonant modes and resonant curves of droplets for study interface properties.
- Surface tension measured from the resonant frequency of pendant hemispherical drop.

## GRAPHICAL ABSTRACT

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## ABSTRACT

A new technique for examination of interfacial electric phenomena on droplet surface in real time is proposed. The technique is based on measuring the resonant frequency of spherical and hemispherical pendant droplets driven in oscillations by a modulated electric field. The amplitudes of forced oscillations are detected by an optical system comprising a low power laser beam and a photodiode. The surface tension and viscosity can be evaluated from the obtained resonant curves.



## 1. Introduction

Recently, we have shown that pendant droplets can easily be driven into oscillations by applying an external electric field [1,2]. Droplets can be driven into oscillations by different means: by piezoelectric transducer [3], by nozzle jet [4], by sudden interruption of high voltage, providing damping oscillations [5], by periodic interruption of high voltage providing steady-state oscillations [6], etc. Many authors have used resonant droplet oscillations to retrieve information for the surface properties of the liquid droplet. Meyer et al. [7] have used decaying resonant oscillations provoked by piezoelectric driver acting upon the supporting nozzle to obtain information about surface tension and decaying constant. The possible pitfalls in defining the resonant frequency with the oscillating drop technique have been discussed by I. Egry et al. in a comprehensive and useful review paper [8]. In the present work a technique is presented to provoke oscillations of a hanging droplet by interfacial dielectric force, acting directly upon the droplet surface. The parameters of the resonant curve (resonant frequency and half-width) have been used as indicators for the surface tension and liquid viscosity.

## 2. Experimental setup

The experimental setup is shown schematically in Fig. 1. The droplet is formed with the help of a syringe, whereas the syringe piston is driven by a micrometric screw. One of the electrodes is the syringe needle and the second electrode is an aluminum plate

* Corresponding author. Tel.: +359 889006099.
*E-mail address:* zoggy@phys.uni-sofia.bg (N. Zografov).

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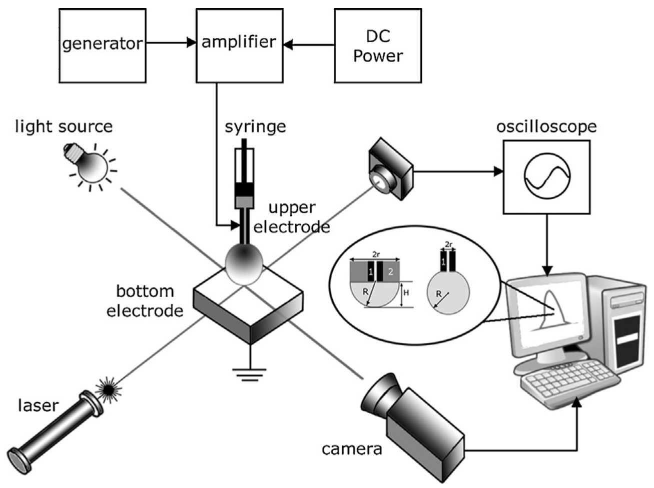


**Fig. 1.** Experimental setup.

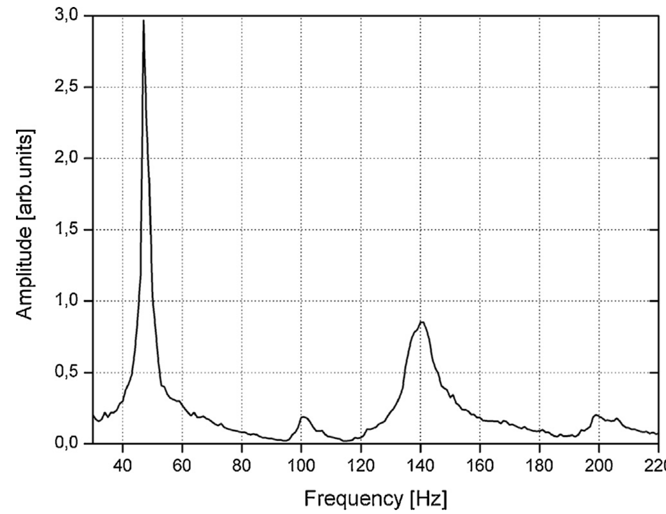


**Fig. 2.** First four resonant modes of deionised water.

below the needle. The droplet is illuminated by a lamp and observed by a video camera connected to a computer, whereas the image contours are analyzed by a software program allowing a precise measurement of the droplet radius $R$ and height $H$. The droplet is also illuminated by a He–Ne laser and the oscillation amplitudes are detected by a photodiode, followed by a digital oscilloscope. The electrical signal from the oscilloscope, proportional to the oscillation amplitude, is fed to the computer for saving and analysis. The driving ac voltage is generated by a generator and fed to an amplifier. A dc voltage is applied additionally to the amplifier by a bias voltage source.

## 3. Electric forces at the interface liquid–air

The electric bond number $N = \varepsilon RE^2/2\sigma$ can be used as a measure for the influence of the electric field on the drop shape. Strong electric fields ($N > 1$) have numerous applications – electrostatic levitation of droplets, multiphase separation, liquid jetting, electrowetting, electric dispersion of liquids into small micron droplets, etc. Weaker electric fields ($N < 1$) can be used for excitation of small amplitude interface oscillations.

The driving electric force is due to the jump of the normal components of the electromechanical stress tensor at the interface liquid–air. The pressure difference across the interface of a droplet can be evaluated by taking the linear integral of the gradient of the force density:

$$\Delta P = \frac{3}{2}\varepsilon_0 E^2 \frac{\varepsilon - 1}{\varepsilon + 2} \quad (1)$$

An electric field can be used as a driving force at the interface liquid–air both for charged and insulating liquids, provided the inequality $\varepsilon > 1$ holds true.

The dielectric force is quadratic to the electric field $E$, while the Lorentz force $F = -qE$ is linear to $E$. If we apply a combination of dc and ac electric fields the dielectric force will have components oscillating at the frequency of the ac electric field and at the second harmonic, as can be seen from simple trigonometric relations:

$$\text{If} \quad E = E_{dc} + E_{ac}\sin\omega t$$

$$\text{then} \quad E^2 = E_{dc}^2 + E_{dc}E_{ac}\sin\omega t + 0.5E_{ac}^2(1 - \cos 2\omega t) \quad (2)$$

The first term causes constant in time deformation, the second term causes force oscillating at the frequency of the field and the third term is a force oscillating at double frequency.

Recently we have shown that pendant droplets can easily be driven into oscillations by applying relatively small ac voltage (about tens of volts), accompanied by a higher dc voltage (about 100 V) [1,2]. The dc voltage is used to enhance the signal and to linearize the quadratic dependence of the driving force on the electric field. Thus, the oscillation frequency coincides with the frequency of the driving electric field.

## 4. Forced oscillations

The oscillating drop technique for measuring properties of the liquid and the interface of the droplet has been analyzed and reviewed widely in literature [7,8]. Most theoretical analyses, starting with the pioneering work of Rayleigh [9] treat ideal spherical droplets, unaffected by external forces and supporting surfaces.

Forced oscillations disturb the equilibrium state of the droplet and the deviations are detected by an optical system comprising weak laser beam and a photodiode. To avoid instability due to laser beam adjustments, the laser beam cross section is widened by a telescope, surpassing the size of the examined droplet.

The obtained dependence of the amplitudes of the droplet oscillations on the frequency describes a resonant curve – Fig. 2, from which the resonant frequency and the resonant width can be determined with high accuracy. The resonant curve depends on surface tension, on droplet volume and on force frequency. Keeping two of these parameters constant and scanning continuously the third parameter allows one to describe the resonant curve which gives flexibility of experiments to obtain different information for the liquid. The resonant frequency is related to the surface tension through the Rayleigh formula, while the resonant width is related to attenuation and viscosity through the $Q$-factor of the oscillating system. The frequency of the $n$th resonant mode for a perfect sphere, calculated by Rayleigh is:

$$f_n^2 = n(n-1)(n+2)\frac{\sigma}{4\pi^2\rho R^3} \quad (3)$$

The lowest possible mode for $n = 2$ is called Rayleigh frequency:

$$f_2(R) = \sqrt{\frac{2\sigma}{\rho\pi^2 R^3}} \quad (4)$$