

Electrohydrodynamic oscillatory deformation of viscoelastic droplets as an interfacial microrheometer

Chintak Kamalesh Parashar¹, Omkar S Deshmukh¹, Dipankar Bandyopadhyay^{1*}

¹ Indian Institute of Technology Guwahati, Guwahati, Assam-781039 India,

*dipban@iitg.ac.in

Summary:

A water-based polymer droplet suspended in silicone oil is driven by an AC electric field and used as a non-contact rheological sensor. The work links interfacial Maxwell stress, transient droplet deformation and oscillatory relaxation to viscosity, interfacial tension and elasticity. A perfect-conductor approximation is justified within the experimental range frequency, enabling a compact electromechanical description. The resulting electrohydrodynamic response provides a compact route for classifying liquid-like and solid-like behaviour as well as measure of interfacial tension during relaxation behavior at small volume.

Keywords: electrohydrodynamics, droplet rheometry, viscoelasticity, Maxwell stress, microfluidic sensing

Title

Electrohydrodynamic oscillatory deformation of viscoelastic droplets as an interfacial microrheometer.

Background, Motivation and Objective

Droplet electrohydrodynamics provides a sensitive way to convert electric forcing into a measurable mechanical response through interfacial stress. Classical work by Taylor established that electric-field-induced circulation and deformation depend on the electrical properties of the two phases [1]. More recent studies have expanded this framework to transient AC excitation, finite charge relaxation and high-fidelity small-deformation theory [2,3]. In parallel, microfluidic rheometry has emerged as an attractive route for low-volume characterization of complex fluids [4]. The present work combines these ideas and asks whether the time-dependent deformation of a single droplet can act as a compact sensor for viscosity, interfacial tension and viscoelasticity. The objective is to translate droplet shape dynamics, phase lag and recovery into rheological descriptors that are relevant for publication oriented screening of complex liquids.

Description of the New Method or System

A water-based polymer droplet was suspended in silicone oil and excited at 300 V rms over an external frequency range of approximately 15-500 Hz as shown in Fig. 1. Time-scale analysis using the Maxwell-Wagner relaxation time, bulk charge relaxation and the frequency-dependent Clausius-Mossotti factor indicates negligible

polarization lag in this operating window; the droplet can therefore be treated as a nearly perfect conductor. Under electroquasistatic conditions, the electric field generates a normal Maxwell stress jump at the interface, with the strongest tensile stress at the poles and weaker response at the equator [1,2]. The deformation signal is quantified through the standard deformation parameter as a time dependent strain.

Results

Experiments were carried out by varying droplet diameter, viscosity, viscoelasticity, interfacial tension and thereby sample rheology. The transient response shows a DC component in the mean deformation and an AC component in the oscillatory amplitude, consistent with AC EHD theory [2]. Validation against Taylor-type small-deformation behaviour indicates that larger droplets achieve larger peak deformation because the total interfacial electrical loading increases with size, whereas the oscillation magnitude is governed primarily by the surrounding medium viscosity. The creep time increases with both droplet size and oil viscosity, showing that hydrodynamic damping dominates the time required to reach steady oscillation. As the forcing frequency increases, the droplet can no longer follow the field and the oscillation amplitude decreases. For higher elastic droplets the loading and unloading traces nearly collapse, while viscoelastic samples display hysteresis and higher viscous droplets display broader loops, delayed recovery and non-zero area hysteresis. These signatures are consistent with energy storage

and dissipation occurring simultaneously in complex fluids [4]. The relaxation segment after switching off the field is especially informative: fast decay indicates stronger capillary restoration, while slower recovery indicates viscoelastic stress storage and structural reorganization within the droplet

Sensor Implication and Material Classification

The method was examined on DI water, glycerol, honey, sauce, egg white and PVA+borax. Increasing viscosity broadens the temporal response and reduces interface velocity, while increasing elasticity introduces memory between cycles. The most elastic samples exhibit partial recovery after field removal, limit-cycle rotation and oval trajectories with larger eccentricity, all of which are indicative of increasing Deborah number. In this sense, the droplet operates as a soft transducer: the electric field is the calibrated input and the deformation waveform is the sensor output. Compared with a conventional rheometer and DWS measurements, the EHD signal captures the same qualitative progression from fluid-like to solid-like behaviour (as seen in Fig. 1), but with small sample volume and without direct mechanical contact. This makes the platform attractive for rapid screening of biological and food-like fluids where sample amount is limited and interfacial phenomena cannot be ignored.

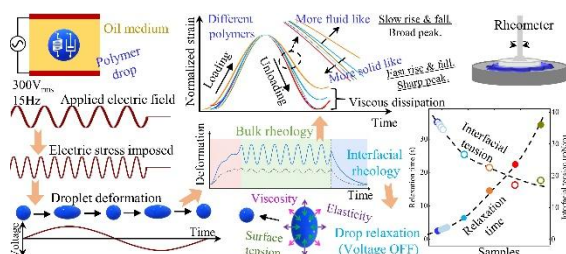


Fig. 1. Schematic of the AC-driven droplet microrheology concept. Interfacial Maxwell stress deforms a conducting polymer droplet in silicone oil, and the resulting waveform is used to infer viscosity and elasticity. Relaxation test is used to infer the surface tension.

Qualitative Material Map

Tab. 1 summarizes the qualitative material progression observed in the study. Low-viscosity samples respond rapidly with narrow loops and negligible recovery, whereas increasingly elastic samples show slower rise and fall, stronger damping and persistent memory during repeated forcing. This trend supports the use of droplet EHD as a compact physical-sensing modality for rheological fingerprinting.

Tables

Tab. 1: Qualitative relation between sample rheology and droplet EHD response

Sample	Dominant property	Observed EHD signature
DI water	High interfacial tension	Fast rise/fall
Honey/Glycerol	Higher viscosity	Incomplete oscillation
Eggwhite/PVA+borax	Strong elasticity; Lowest Interfacial tension	Slow rise/fall; Complete oscillation

References

- [1] G. I. Taylor, Studies in electrohydrodynamics. I. The circulation produced in a drop by an electric field, *Proc. R. Soc. A* 291, 159-166 (1966); doi: 10.1098/rspa.1966.0086.
- [2] A. Esmaeeli, Transient electrohydrodynamics of a liquid drop in AC electric fields, *Eur. Phys. J. E* 41, 135 (2018); doi: 10.1140/epje/i2018-11745-1.
- [3] D. Das, D. Saintillan, A three-dimensional small-deformation theory for electrohydrodynamics of dielectric drops, *J. Fluid Mech.* 914, A22 (2021); doi: 10.1017/jfm.2020.924.
- [4] F. Del Giudice, P. S. Wilson, A review of microfluidic devices for rheological characterisation, *Micromachines* 13, 167 (2022); doi: 10.3390/mi13020167.