Interfacial transients at a moving liquid meniscus[1]

T. B. Jones, K.-L. Wang, and S. Bei
Department of Electrical & Computer Engineering
University of Rochester, Rochester, NY 14627 (USA)
email: jones@ece.rochester.edu

Microfluidic schemes exploiting electromechanical forces such as electrowetting-on-dielectric (EWOD) and dielectrophoresis (DEP) combine speed, geometric simplicity, and voltage-based control. Static models for the electrical forces driving these phenomena are now well established, but the dynamics, and in particular, the electric-field coupled behavior of the moving contact line, are not nearly so well understood. Contact line effects encompass the apparent contact angle itself, plus the profile of the moving interface, interfacial vibrations due to AC voltage, and an apparent dynamic "line friction" that impedes forward motion of the liquid front.

In the past, we used Pellat's experimental geometry, shown in Fig. 1, to observe transient height-of-rise $h(t)$ as a function of voltage, electrode spacing, and frequency [1]. In the present work, we report some interfacial behavior exhibited by the rising liquid column, using a high-speed camera to record the details of the time-dependent meniscus. These studies are motivated by our observation that the onset of saturation is delayed in time during the transient, upward motion. At voltages below the static saturation limit, a reduced-order dynamic model incorporating velocity-dependent contact line friction accurately describes the time course of $h(t)$ throughout the transient rise. In contrast, at higher voltages the upward motion deviates significantly from prediction, but does so only after 200 to 500 ms have lapsed. By this time, the liquid column has risen half way or more to its final value. Before this abrupt deceleration, the data match the predictions of the model very well. The rise time of the voltage is very short compared to the characteristic time of the upward motion, so we conclude that saturation occurs abruptly, with the effect of suddenly reducing the driving force to the saturated limit value reflected in previous, static measurements.

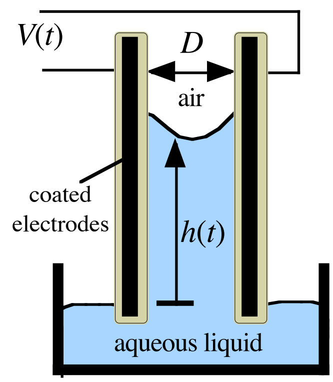

Fig. 1. Modified Pellat apparatus for aqueous liquids has vertical, parallel electrodes coated with a thin dielectric layer.

We hypothesize that this delayed onset of saturation is linked to motion of the meniscus. Possible mechanisms include (i) strong viscous shear flow near the contact line resulting from the non-slip condition at the walls and/or (ii) vigorous interfacial surface waves caused by the AC electric field. In this paper, we focus on the second of these possible explanations, surface waves, which depend on the magnitude and frequency of the applied voltage and the spacing of the electrodes. The experiments cover voltages from 25 to 250 V-rms at frequencies between 10 Hz and 100 kHz and electrode spacings of 0.5, 1.0, and 2.0 mm. All videos were recorded at 1000 fps, which is found to be adequate to capture the important dynamics. Individual video frames were processed with a MATLAB™ program to obtain quantitative data such as dynamic contact angle values and meniscus profiles. With our microscope and camera, the per pixel resolution is 10 to 12 μm.

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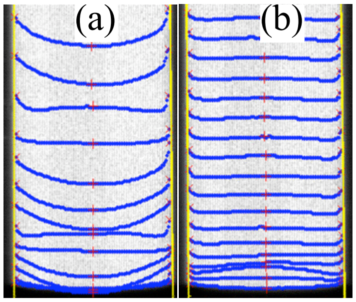

Fig. 2. Sequences of meniscus profiles at 1 ms intervals from videos. The electrode spacing $D = 0.5$ mm, voltage = 150 V-rms, frame rate = 1000 fps. (a) 100 Hz. (b) 100 kHz.

The videos reveal behavior comprised of a superposition upon the transient, electromechanically-driven, liquid rise of rather complex, time-dependent interfacial dynamics. In the electrowetting regime at frequencies f << 20 kHz, the liquid behaves as a perfect conductor, concentrating the electric field in the dielectric layer [2]. The contact angle rapidly decreases when the voltage is applied and the meniscus assumes a concave profile within ~1 ms. Once the liquid starts to rise, the meniscus oscillates between concave and convex, with corresponding fluctuations of the contact angle. Refer to Fig. 2a. For f >> 20 kHz, well into the DEP regime where the liquid behaves as a dielectric and the electric field penetrates the liquid, the meniscus becomes convex in the first few milliseconds before the contact line begins moving. After ~3 ms, the contact line starts to move upward, the contact angle decreases, and the meniscus flattens. Upward motion then proceeds with a roughly constant, slightly convex profile. See Fig. 2b. At f ~ 20 kHz, the dynamic profile exhibits behavior intermediate between the high and low frequency limits just described.

At larger electrode spacings ($D \geq 2$ mm) and frequencies in the range ~50 to ~200 Hz, vigorous side-to-side sloshing of the meniscus is observed. This hydrodynamic resonance presumably results from a parametric interfacial instability. Fig. 3 shows how this sloshing superimposes itself upon the upward motion of the liquid column. Note what appears to be an alternating, slip-stick motion of the two contact lines on the opposed vertical electrodes.

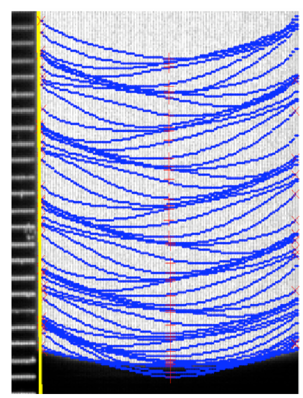

Fig. 3. Sequence of super-imposed meniscus profiles captured at 1 ms intervals. Electrode spacing D = 2 mm; voltage is 150 V-rms at frequency f = 100 Hz.

The profiles in Figs. 2 and 3 reveal complex interfacial motions that we have analyzed using spatial Fourier series. Underpinning this approach is an assumption that the interfacial dynamics relate to classical capillary surface wave hydrodynamics. Our findings generally support this idea, though there are some interesting surprises. We define the interfacial motion $\xi(x,t)$ in terms of the height-of-rise $h(x,t)$, where $0 \leq x \leq D$.

$$\xi(x,t) = h(x,t) - h_{\mathrm{avg}}(t)\ , \ \text{where}\quad h_{avg}(t) = \frac{1}{D}\int_0^D h(x,t)\,dx \tag{1}$$

Based on observations of the high-speed videos, we hypothesize a partition of the interfacial motion into even (capillary) and odd (sloshing) modes, i.e., $\xi(x,t) = \xi_{\mathrm{cap}}(x,t) + \xi_{\mathrm{slosh}}(x,t)$, where

$$\xi_{\mathrm{cap}}(x,t) = \sum_{n=\mathrm{odd}} \xi_{\sin,n}(t)\,\sin(k_n x) + \sum_{n=\mathrm{even}} \xi_{\cos,n}(t)\,\cos(k_n x) \tag{2a}$$

$$\xi_{\mathrm{slosh}}(x,t) = \sum_{n=\mathrm{odd}} \xi_{\mathrm{slosh},n}(t)\,\cos(k_n x) \tag{2b}$$

and $k_n = n\pi/D$ for integer n. Standard integrals define the time-dependent coefficients in Eq. (2a,b).

$$\xi_{\sin,n}(t) = \frac{2}{D}\int_0^D \sin(k_n x)\left[h_{\mathrm{data}}(x,t) - h_{\mathrm{data-avg}}(t)\right]dx,\ n = \mathrm{odd} \tag{3a}$$

$$\xi_{\cos,n}(t) = \frac{2}{D}\int_0^D \cos(k_n x)\left[h_{\mathrm{data}}(x,t) - h_{\mathrm{data-avg}}(t)\right]dx,\ n = \mathrm{even} \tag{3b}$$

$$\square_{\mathrm{slosh},n}(t) = \frac{2}{D}\int_0^D \cos(k_n x)\left[h_{\mathrm{data}}(x,t) - h_{\mathrm{data-avg}}(t)\right]dx, \quad n = \mathrm{odd} \tag{3c}$$

Because in the present case all meniscus data $h_{\mathrm{data}}(x,t)$ are extracted from bitmaps of individual video frames, these integrals are replaced by summations.

Results at lower frequencies are shown in Fig. 4. The average meniscus height $h_{\mathrm{avg}}(t)$ has been superimposed to track the upward motion. Fig. 4a (f = 50 Hz) reveals n = 1 even (capillary) and odd (sloshing) modes oscillating at 2×50 = 100 Hz. At f = 200 Hz (Fig. 4c), both n = 1 and n = 2 capillary components are present at 400 Hz, and the n = 1 sloshing mode is virtually absent. On the other hand, at f = 100 Hz excitation (Fig. 4b), a strong n = 1 sloshing component at 100 Hz is present, while a much weaker n = 1 capillary component oscillates at $2f$ = 200 Hz. The double frequency components dominating in Figs. 4a and c are certainly as expected, given that the electrical force is proportional to the square of the electric field. The strong n = 1 sloshing mode at sub-harmonic frequency 100 Hz is probably the result of parametric instability. In fact, the calculated resonant frequency of this mode is 87 Hz, rather close to 100 Hz.

The causal connection of these interfacial motions to electrowetting saturation is not yet established, but the present line of investigation should help identify the conditions upon frequency, voltage, and electrode spacing leading to the most vigorous wave dynamics. In future experiments, we will vary frequency in small increments to map out parametric instabilities and/or driven resonances. If the hypothesis is true that surface motions inhibit saturation, then the same conditions leading to vigorous interfacial motions should correspond to the largest beneficial effect upon saturation.

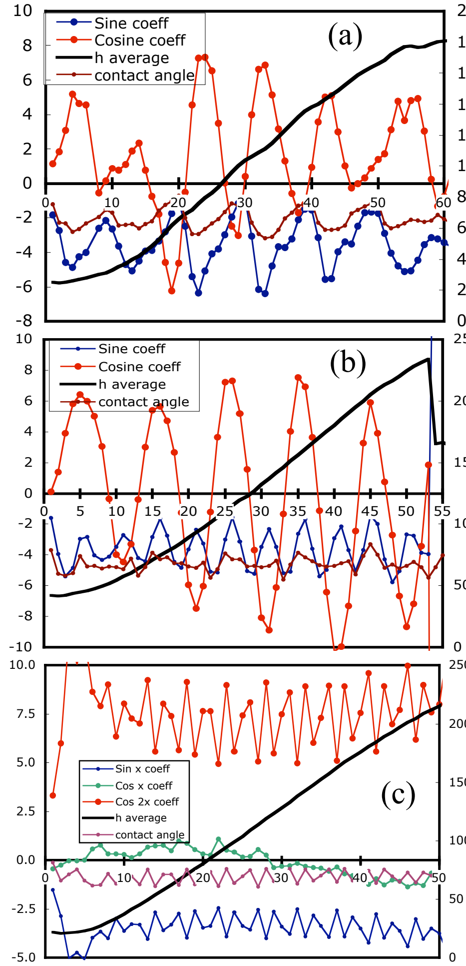

Fig. 4. Fourier components extracted from meniscus data obtained from video sequences. Spacing: D = 2 mm; voltage: V = 150 V-rms; liquid: DI water. Black curves are provided to show simultaneous time course of the rising meniscus. (a) f = 50 Hz. (b) f = 100 Hz. (c) f = 200 Hz.

References

[1] K-L Wang and TB Jones, "Electrowetting dynamics of microfluidic actuation", Langmuir, vol. 21, pp. 4211-4217, 2005.

[2] TB Jones, K-L Wang, and D-J Yao, "Frequency-dependent electromechanics of aqueous liquids: electrowetting and dielectrophoresis," Langmuir, vol. 20, pp. 2813-2818, 2004.

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