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ANALYSIS OF ERROR SENSITIVITY OF A SYSTEM FOR ELECTROWETTING FORCE MEASUREMENT

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ABSTRACT

Electrowetting systems are commonly studied by measuring contact angle changes with applied voltage. However many applications such as digital droplet manipulation require information about the force applied to a drop to improve performance. This paper analyses a previously demonstrated method of measuring the electrowetting forces to estimate the sensitivity of force measurements to potential errors such as droplet evaporation, variation in volume, and alignment accuracy. The most significant force errors are introduced by uncertainty in droplet volume as by evaporation. However, analysis shows that this can be controlled by lowering the measurement tip to compensate for evaporation. Errors in tangential force due to alignment are shown to be small for alignment errors below 1º.

INTRODUCTION

Miniaturization increases surface to volume ratios bringing challenges in control of surface and surface energies [1]. Microfluidics has tremendous opportunities with its capability to handle small volumes of liquids to impact diverse fields including chemical synthesis [2], chemical/biological measurement [3, 4], and microscale cooling [5]. A fundamental issue in microfluidics is the movement of fluid volumes as desired. Micro pumps offer one solution. However micro pumps require a variety of lithography steps for fabrication. This method helps in only a continuous flow and introduces reliability challenges [6]. Electrowetting is a promising method to realize the motion, dispensing, splitting and mixing of single droplets in a microfluidic system without the need of any mechanical or fault prone components. Instead the interfacial energy of the liquid-solid interface is adjusted locally through applied voltages. [1] It is most commonly implemented with a dielectric layer between the electrodes to reduce electrochemical reactions as illustrated in FIGURE 1. In electrowetting on a dielectric (EWOD), the contact angle (θ_o) as a function of the applied voltage (V) can be related to the dielectric thickness (δ) and dielectric strength (ε_0,ε_R) as proposed by the Young Lippman equation [1].

$$Cos\theta_1 \quad = \quad Cos\,\theta_0 + \frac{\varepsilon_0 \varepsilon_r V^2}{2\gamma_{lv}\delta} \qquad (1)$$

Where θ_0 is the initial contact angle with zero voltage and γ_{lv} is the surface energy of the liquid vapor interface. This model provides a good prediction below the saturation voltage.

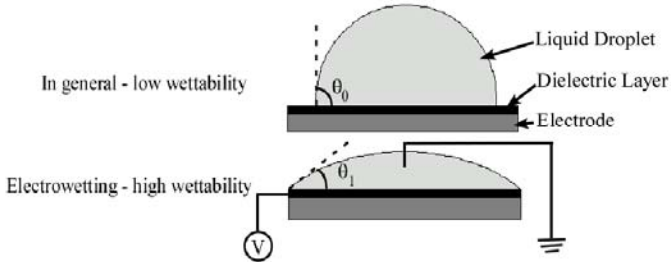

FIGURE 1 Representation of the variation of contact angle with applied voltage through the electrowetting effect.

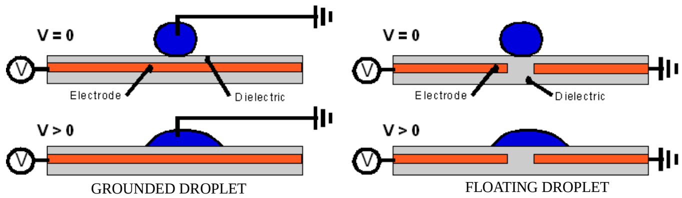

FIGURE 2 Most commonly employed configurations in Electrowetting.

Electrowetting applications utilize several different electrical arrangements. FIGURE 2 shows two configurations: grounded droplet and floating droplet.. In the grounded droplet method, the liquid is grounded by direct connection to an electrode. A lumped parameter model of the electrical circuit is a single capacitor. In the floating droplet, the droplet forms the connection between two series capacitors so that the droplet voltage floats. Droplet voltage is a function of the voltage applied to the circuit and the relative values of the two capacitances.

Both of these configurations can produce an effective force on the liquid both in the lateral and normal direction if the field is nonuniform around the drop. These forces can be used to manipulate droplets. While the forces are of direct interest in many electrowetting applications, previous efforts have not directly measured these forces. Instead, the electrowetting response is assessed by measuring the contact angle of the fluid and/or the capacitance of the fluid/electrode interface. ([7-9] Modeling of the electrowetting response of droplets has been done using Surface Evolver. Surface Evolver calculates the system energy. Forces are found by differentiating the energy with respect to the displacement of interest. [10, 11].

Direct measurement of electrowetting forces would permit improved assessment of electrowetting models. It would also support identification of electrowetting degradation, bubble formation, and erratic behaviors observed in some experiments. [8, 12, 13] It is critical that these degradation mechanisms be identified and characterized in order to design robust electrowetting-actuated processes. This work will review a proposed system for measuring the electrowetting force and present an assessment of the sensitivity of lateral force measurements to potential errors.

NOMENCLATURE

A_L,A_R	Droplet/Electrode area for left and right electrodes respectively.
h	Gap between the measurement plate and the substrate
L	side length of the measurement plate attached to the Hysitron Nanoindenter
W	Edge length of the electrode gap that is below the plate
Y_c	The critical offset after which W varies with displacement when z-axis rotations are significant
V	Voltage. V_T, V_R, V_L refer to total voltage, right electrode voltage, and left electrode voltage respectively.
V_d	Volume of droplet
α	rotational error about z-axis
δ	thickness of the dielectric layer
ε_r	relative dielectric constant of the dielectric layer
ε_o	permittivity of vacuum
γ_{lv}	liquid vapor surface energy
θ_o,θ_1	Contact angle of the drop with zero voltage and nonzero voltage respectively

ELECTROWETTING FORCE MEASUREMENT

Crane et al. [14] demonstrated that a nanoindenter could be adapted to measure these fluid forces with a custom tip. The “floating droplet” configuration illustrated in FIGURE 2 was used with the droplet positioned over two substrate electrodes. A voltage is applied across the electrodes so that both electrical inputs are located on the substrate. At steady state, the resistance of the fluid can be neglected so the drop can be modeled as an electrical circuit of two capacitors in series. Repeatable measurements are obtained by trapping the drop between the substrate and a top-plate that is wetted by the drop. The basic experimental configuration is illustrated in FIGURE 3.

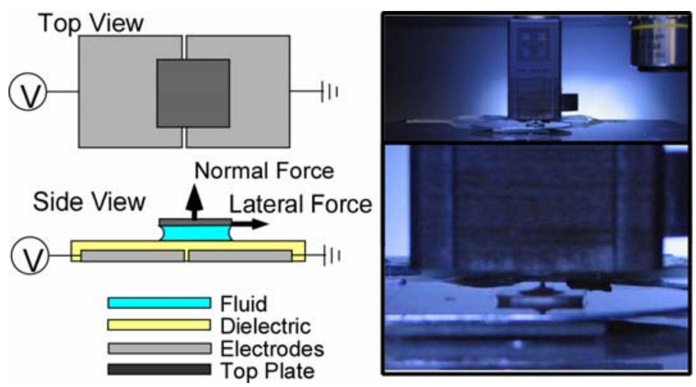

FIGURE 3 Electrowetting force measurement system. (Left) Schematic representation of the system. (Right) Picture of indenter with flat plate installed.

This was implemented by attaching a 9mm x 9mm glass plate to a modified tip of a Hysitron Triboindenter. The Triboindenter measures the forces on the plate normal to the substrate and in one in-plane direction. Since water wets the glass plate, drops are trapped between the plate and the substrate. As the gap between the plate and substrate decreases, the drop/substrate contact area closely approximates the area of the top plate and does not change significantly under an applied voltage [14].

With a constant voltage across the electrodes, the voltage at each drop/electrode interface will depend on the capacitance of the two capacitors. To first order, the capacitance can be modeled as a parallel plate capacitor. The capacitance is a function of the area of the drop over the electrode. This value changes with position. If the dielectric layer has a constant thickness and dielectric constant, the voltage induced on the left and right electrode at steady state can be calculated as

$$V_L = \frac{A_R}{A_L + A_R} V_T \quad V_R = \frac{A_L}{A_L + A_R} V_T \tag{2}$$

Where V_T is the total voltage applied to the system, A_L and A_R are area of the electrode under the droplet on left and right electrodes respectively. The areas depend on the position of the droplet relative to the electrode gap. Hence voltage on each side of the electrode is a function of area which in turn depends on droplet position.

When a voltage is applied, the equilibrium position of the plate changes. Since the plate is restrained by the tip holder from moving toward the equilibrium, the fluid applies a force on the plate in the direction of the minimum energy configuration. Due to the symmetry of this arrangement, the forces should be predominately in the lateral ('Y') and normal ('Z') directions. The magnitude of the lateral forces as predicted by numerical models can be closely approximated with simple formulas for the ideal case [14]. Given a relatively thin drop, the force is linearly related to the distance (x) of the plate from being centered over the electrode gap by

$$F_x = -\frac{\varepsilon_0 \varepsilon_R}{\delta} V_T^2 x \tag{3}$$

Although testing has shown that the experimental setup can measure the electrowetting forces, it is unclear how closely parameters such as alignment accuracy, droplet volume, and plate/substrate gap must be controlled. This paper will use numerical models to estimate the sensitivity of the system to these variations.

NUMERICAL MODELS OF ELECTROWETTING FORCE

The test configuration was modeled using Surface Evolver-a powerful program for finding surface equilibrium conditions by energy minimization. [11, 15] The electrowetting effect was modeled using Equation 1 and 2 with the areas calculated directly by Surface Evolver. The basic Surface Evolver geometry and the model coordinate system are shown in FIGURE 4. For each point, the fluid volume was fixed and the top plate position held constant while Surface Evolver calculates the equilibrium surface position. The forces at these points were calculated by numerical differentiation of the system energy with respect to displacement. This model was adjusted to simulate the impact of different fluid volumes, evaporation of fluid, and substrate/plate alignment errors on the output forces. The model parameters in TABLE 1 were used for all analysis except where indicated.

Initial tests confirmed that gravity had negligible impact on the forces of interest due the large surface areas of the droplet in the test configuration. Therefore, gravitational effects were not included in the reported results. Analysis convergence was controlled using an automated script. Convergence of the solutions was manually checked for extreme parameter values.

TABLE 1 Surface Evolver Model Parameters

Variable	Value
Gap width	2 mm
Surface Energy (γ_{lv})	.072 J/m^2
Liquid/Substrate Contact Angle (θ_o)	110º
Liquid/Measurement Plate Contact Angle	20º
Plate side length (L)	9 mm
Dielectric constant (ε_r)	2.1
Dielectric thickness (δ)	2.1 μm
Voltage (V)	100 V
Drop Volume (V_d)	47 μl
Plate-Substrate Gap (h)	580 μm

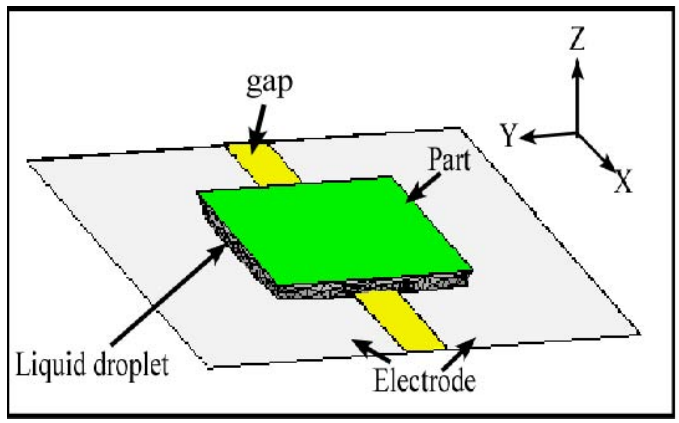

FIGURE 4 Surface Evolver model for force analysis on electrowetting.

RESULTS

The force model (Equation 3) assumes that the plate and substrate are parallel and that the plate edges are aligned with the gap. Further, the force equation assumes that the fluid completely wets the plate and is thin enough so that the contact area between the fluid and the substrate closely approximates the area of the plate. The accuracy of these assumptions was assessed by comparing force measurements under different alignment errors, volumes, and z-heights. The results are summarized below.

Rotational Misalignment

Initial experimental results from the electrowetting force measurement system showed that force measurements were in the expected range. Additionally, analysis of a perfectly aligned substrate/plate has shown good agreement with analytical force predictions. However, the sensitivity of the measurements to substrate/plate misalignments must be assessed in order to identify the conditions under which suitable measurement accuracy can be obtained. Y-force is the primary measurement output of the sytsem, but z-forces are also recorded and might provide additional process insight. The sensitivity of both forces to angular misalignments will be considered. FIGURE 5 illustrates the three different angular misalignments.

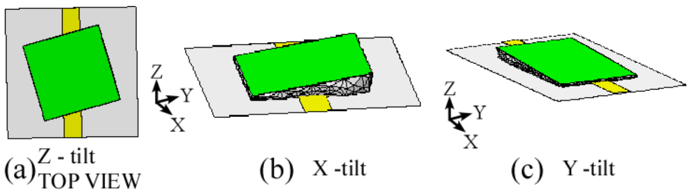

FIGURE 5 Illustration of possible angular misalignments of plate relative to substrate electrodes.

Z-axis rotations increase the length of the line that intersects the electrode edges. Since the y-force is related to the change in the partial derivative of system energy with respect to y-position, this changes the slope of the y-force/y-displacement relationship, but it remains linear over a large range. However, above a critical displacement level, the force relationship changes. The critical offset is given by

$$Y_C = \left(L\frac{\sqrt{2}}{2} Cos\left(45+\alpha\right) \right) - {gap}/{2} \qquad (4)$$

where W is the edge length of the electrode gap that is below the plate, Y_c is the critical offset after which W varies with displacement. These parameters are illustrated in FIGURE 7 below.

The y-axis force variation with z-axis rotations is summarized in FIGURE 7(a). If the offset is maintained below the critical y-offset value, the y-force variation is less than 0.5% for a 2º rotation and 2% for a 5 º rotation.

The y-force was calculated for y-axis rotations of 0, 0.1,1, and 5º as seen in FIGURE 7(c). The results showed that measurement accuracies are relatively insensitive to rotations about the y-axis with less than 1% error for a five degree rotation.

While rotations about the y-axis impact both electrodes symmetrically, x-axis rotations will increase the fluid thickness on one side while decreasing it on the other. Thus, y-force is most sensitive to x-axis rotations as seen in FIGURE 7(e). Even a 0.5 degree error will introduce an average error of approximately 1%. Average errors rise to 3.3% and 6.6% for 2 and 5 degree rotations respectively.

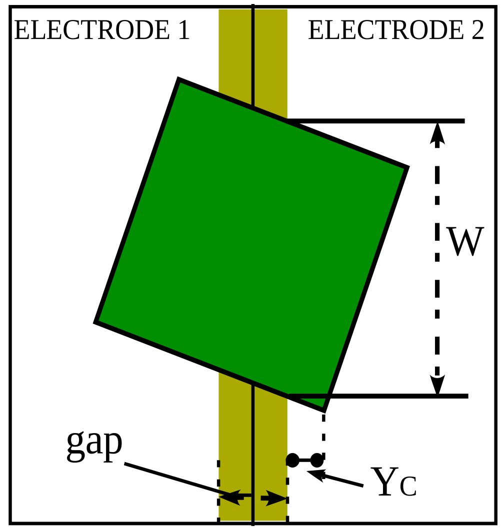

FIGURE 6 Illustration of Z-tilt and the critical y-offset.

If the plate and substrate are well-aligned, the z-force is relatively stable with displacement in the y-axis. However, while y-forces were found to be relatively insensitive to all misalignments, normal (z) forces were very sensitive to x-axis alignment (FIGURE 7(f)) with 20% errors from 1º angular misalignments. Given this sensitivity, the z-force measurements are not easily used to evaluate the surface in absolute terms. However, they may be useful for determining changes with time due to droplet evaporation or dielectric degradation.

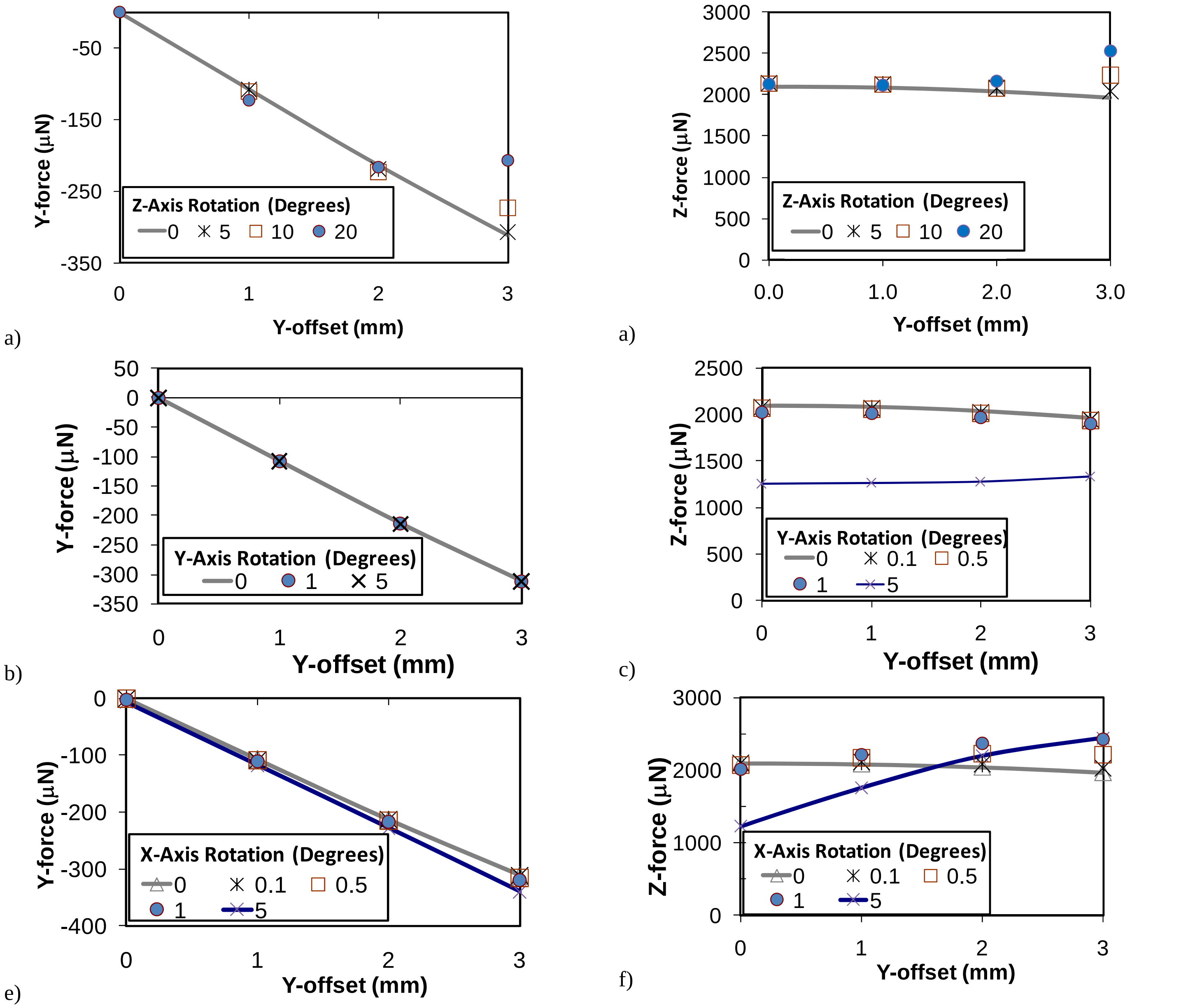

FIGURE 7 Impact of alignment errors on electrowetting forces. Plots (a),(c), and (e) show the impact of alignment errors in the z-, y-, and x- axis respectively on y-force. Plots (b), (d), and (f) show how z-forces vary with errors around the z-, y-, and x- axis respectively.

Droplet Evaporation

Droplet volume is an important parameter in the models. The basic model condition of 47 µl and a 580 µm plate to substrate gap were selected so that the droplet would exactly fill the volume between the top plate and the substrate. This is critical to meet the assumptions of the measurement method, but most testing fluids such as water are subject to evaporation during testing. What impact might this have on the force measurements? FIGURE 8(a) shows how the y-force measurement changes with volume if the gap is maintained constant. This change quickly exceeds 1% of the total force and could impact the accuracy of the measurements. However, if the gap is decreased as the drop evaporates so that the ratio of projected volume to drop volume is maintained near unity, the change in force due to evaporation is dramatically reduced. A 6% volume decrease by evaporation would only decrease the force measurement by 0.6%.

The evaporation with time can be tracked using the z-force measurements. As seen in FIGURE 8(b), the z-force changes linearly with volume so that z-force changes can be used to direct adjustments to the plate height to maintain the desired V_d/hL^2 relationship.

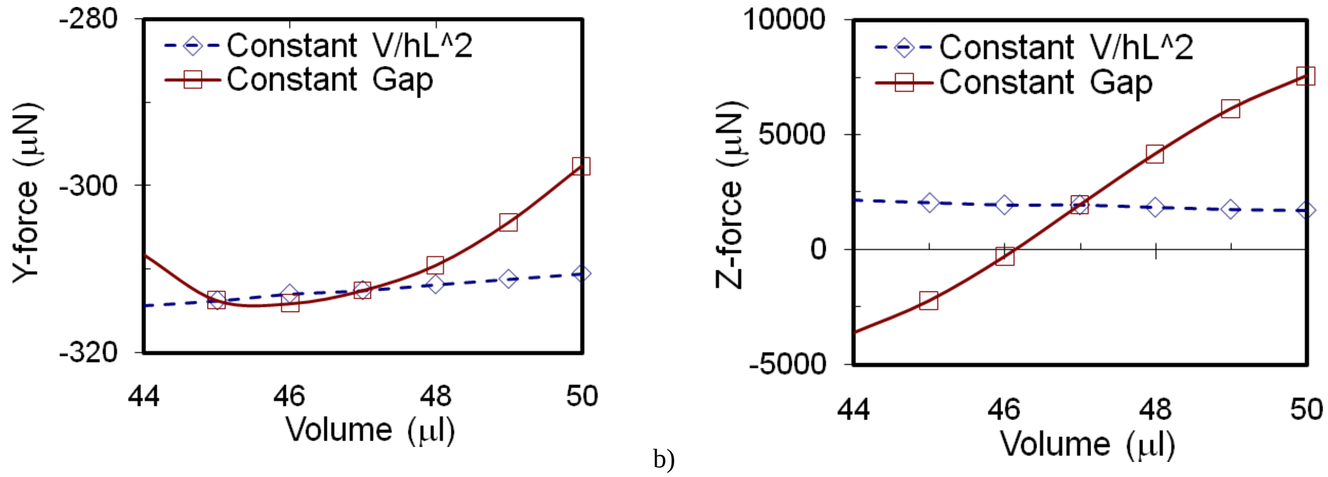

FIGURE 8 Variation in y-forces (a) and z-forces (b) with changes in volume. The figures compare the use of a constant substrate/plate gap to adjusting the gap to maintain a V/hL^2 ratio of unity. All analysis assumes a y-offset of 3 mm.

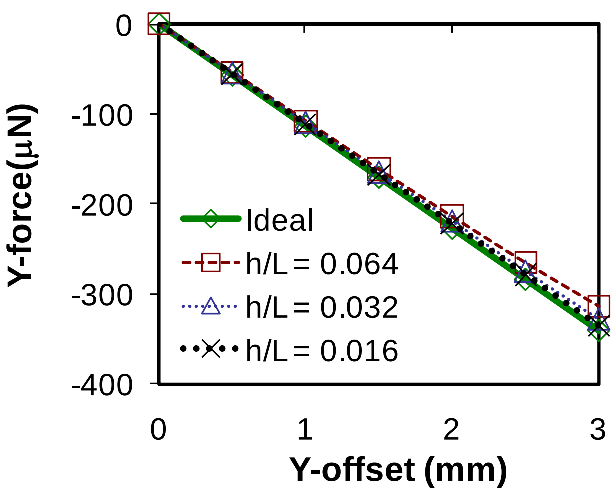

FIGURE 9 Impact of gap height (*h*) on accuracy of y-force equation. As the relative gap height (*h*/*L*) decreases, the experimental system y-force is better modeled by Equation 3.

Substrate/Plate Gap

The key to accurate interpretation of the force measurements is to closely approximate the desired idealized conditions. The criteria that the substrate/fluid contact area closely match the area and shape of the top plate is sensitive to the droplet volume and the gap between the substrate and plate. The relative size of the substrate/plate gap affects the force measurements even when controlling for the volume ratio because it changes the accuracy of this approximation. FIGURE 9 shows that as fluid volume decreases the y-forces more closely approximate the idealized prediction of Equation 3. The average deviation from the analytical predictions decreased from 6% at *h/L* of 0.064 to just 2% at *h/L* of 0.16.

DISCUSSION OF RESULTS

The Surface Evolver analysis of the Electrowetting force measurement system provides important guidance to the design and execution of a testing process. First, alignment of the measurement plate to the substrate electrodes must be achieved to within five degrees in the y-axis and z-axis rotations, but much closer alignment is required about the x-axis. In general, it is desirable to maintain alignment in all axes to within 1º with high accuracies in the x-axis if possible. This would maintain measurement errors below 1%. Such alignment could be achieved by in situ mounting of the plate using the substrate as the alignment guide.

Droplet evaporation can be a major challenge to long time period measurements. Over short periods, the gap *h* can be adjusted to offset evaporation, but over large time periods the range of the piezoelectric z-actuation will be insufficient. Such tests may require a technique such as submersion in oil to reduce the evaporation rate.

The analysis shows that for the substrate/plate gaps analyzed, the force predictions deviate linearly from the predictions of Equation 3. While the approximation is good for very small droplets, evaporation may be difficult to manage at the smallest drop sizes. Additionally, the sensitivity of force measurements to alignment errors might increase at very small gaps as small rotational errors about the x-axis or y-axis could cause large differences in plate/substrate gaps from one side of the plate to another. Instead, a scaling factor can be used to adjust Equation 3 for finite substrate/plate gaps. This scaling factor could be determined analytically and verified experimentally.

CONCLUSIONS

Numerical analysis of a system for measuring forces generated by electrowetting has been used to establish guidelines for accurate measurements. This analysis has shown that angular alignments of the measurement plate and the substrate should generally be maintained below 1º, but this guideline can be relaxed for some misorientations. Volume variation is shown to be a significant source of error, but if the fluid volume to projected volume ratio is maintained near unity, the measurements show good stability. These numerical results will be used to direct refinement of the measurement techniques.

ACKNOWLEDGEMENTS

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