Liquid lens based on electrowetting: a new adaptive component for imaging applications in consumer electronics

Jerome CRASSOUS **, Claude GABAY ***, Gaetan LIOGIER *, Bruno BERGE **

* Varioptic, 8B rue Hermann Frenkel, 69007 Lyon; France.
** ENS-Lyon, 46 allée d'Italie, 69007 Lyon, France; +33 472 72 80 00

1.1. ABSTRACT

A new technology for focus variation with direct electric control without moving part will be presented. The technology relies on an interface between two non-miscible transparent liquids, which can be deformed by electrowetting. This technology has been developed since 10 years in the lab and starts to be available commercially, with the following characteristics: large amplitude of dioptic correction (20 dioptres for a 5mm pupil size), fast response, small power consumption and good transmission in the visible range, clear pupil 1-10mm diameter. This paper will show the basic principle, as well as the physical limitations and optical aberrations due to differential thermal expansion of the two liquids in the cell. Experimental measurements made with a Schack Hartmann wave front analyzer will be presented, as well as numerical simulations of the liquid-liquid interface. Applications will be discussed, mainly in consumer electronics.

Keywords: Liquid lens, focus control, liquid actuator

1. INTRODUCTION

Recently there has been a lot of effort to introduce new adaptive optical components for wavefront control and modifications. These actuators have been using several physical principles: among them the piezo effect to deform mirrors, or applying gradients of electric fields to induce refractive index gradients in liquid crystals slabs1, etc.

Another way of approaching the problem has been recently demonstrated when using the liquid-liquid deformation using electrowetting principle2,3: two non miscible liquids with same densities form a natural liquid-liquid interface which can produce an efficient light refraction. Changing the shape of the liquid interface has been shown to be easy and reversible when using the principle of electrowetting4-7: the solid surface which realizes the supporting body for the fluid-fluid interface is made from an electrode with an insulator/hydrophobic layer. Applying a voltage displaces the liquid/liquid/solid line (perimeter of the drop) achieving the focus change through a meniscus curvature change.

One of the key point of the technology relies on the fact that both liquids have the same density. In this paper we will consider the thermal effects due to differences in the coefficient of thermal expansion of the two liquids. This makes a strong physical limitation on the practical size of the lens which could be achieved with liquid/liquid interfaces.

2. THEORETICAL DESCRIPTION OF THE GRAVITY EFFECTS

1.2. Problem description

The lens configuration which we are interested in this paper is described in the figure 1: a cone recess is made of a metallic material (usually stainless steel=ss). This cone is covered with an insulator/hydrophobic film, thickness e and
dielectric constant $\varepsilon$. One of the liquid (oil) is non-conducting, while the other one (water) is a conductor. The figure 1a shows the deformation of the interface due to the externally applied electric voltage. At low voltage the meniscus curvature is directed towards the cone large opening. The lens is then divergent. Applying voltage displaces the interface which becomes progressively convergent (see fig. 1).

![Figure 1: (a) principle of the liquid lens: two non miscible liquids are trapped between two glass windows. The liquid liquid interface moves from continuous ($V=0$) to the dotted line when voltage is applied. (b) influence of a density mismatch between the two liquids on the liquid-liquid interface: spherical when the liquids densities are matched (continuous line ). distorted mainly by a coma aberration when not matched (dotted line).](image)

In this paper we will analyse the effect of a mismatch of the two liquids densities. The experiments do not show a strong dependency of these thermal effects with voltage, such that we will not consider “cross-talk” between voltage-induced and temperature-induced deformations of the interface.

We present here a 2D calculation, assuming an infinite geometry in the third dimension, before comparing with 3D calculations and experiments.

1.3. 2D-calculations

This calculation assumes that the interface is displaced compared to the no-gravity case by $\xi(h)$. A simple analysis of the Laplace pressure across the interface allows to calculate $\xi$ the displacement of the meniscus as:

$$\xi = \frac{1}{6\lambda_c^2} h^3;$$

Where $\lambda_c=(\gamma\Delta \rho g)^{1/2}$ is the capillary length. $\Delta \rho$ is the difference of the two fluids density, $\gamma$ is the liquid-liquid interfacial tension and $g$ if the gravitational acceleration. Assuming that the lens is vertical, which is the worse situation, then $-\Phi_0/2 < h < \Phi_0/2$, with $\Phi_0$ the diameter of the lens pupil. From that expression one can estimate that an incident planar wave will experience a wave front error (wfe) produced by the distortion of the liquid-liquid interface, which is given by:

$$\text{wfe}(h) = \Delta n/(6\lambda_c^2) h^3;$$

The figure 2 shows the curve type wfe(h).
The curve wfe(h) shows that the density mismatch induces a vertical tilt and a coma aberration. The tilt is given as the dotted line in Fig. 2 by minimizing the rms residual wave front error (wfe) after tilt removal.

Angular tilt = 1/10 Δn (Φ₀/2λc)².

Residual wfe (rms) = 1/120 1/(7)¹/² Δn Φ₀³/λc².

Or if we replace the capillary length by its value:

wfe (rms) = 1/120 1/(7)¹/² Δn Δρg/γ Φ₀³.

The angular tilt is the angle of the wave front to the vertical plane. One can verify that the tilt is well below 1 mrad, which is usually irrelevant. The residual wave front error is the rms value of the wave front error corrected from the tilt. In general the residual wave front error is the really important number to characterize the lens quality. It can be seen that the residual wave front error is mainly coma aberration.

If we suppose that the density mismatch Δρ is induced by a difference in the liquid volumic expansion coefficients Δα between the two liquids, when exploring a temperature range of ΔT, the resulting residual wave front error will be given by:

wfe (rms) = 1.57 10⁻¹ ρg/γ Δn Δα ΔT Φ₀³.

This expression assumes that the density of the liquids has been matched at the middle of the range of temperature of interest. Then the maximum temperature difference to the isodensity point is T/2.

### 3. EXPERIMENTAL RESULTS

The experiments we are showing are made using the configuration of Fig. 1. The cone is made of stainless steel (ss) covered with an insulator and hydrophobic material (here made from an FEP film applied on the ss part by hot-pressure). The insulator film results in a 20µm thick film, dielectric constant about ε=2. The first liquids is made of a water solution containing Na₂SO₄ salt (less than 1%) and the oil phase is made from a mixture of commercial silicone oils.
The difference in the index of refractions is $\Delta n = 0.198$; the difference of coefficients of thermal expansion is measured as $\Delta \alpha = 2 \times 10^{-4} \text{ K}^{-1}$; the interfacial tension is measured $\gamma = 12.5 \text{ mN/m}$ and $\Phi_0 = 5 \text{ mm}$.

The figure 3 shows the experimental results for the residual wave front error as a function of $\Delta T$, the difference of the temperature and $T_0$, the iso-density temperature. The iso-density temperature is the temperature at which the liquids were prepared at the same density (presumably in the middle of the working temperature range). The measurements were conducted using a Shack-Hartmann wavefront analyser (Imagine Optics, France). For details of how the measurements are done, see ref 8. The dotted line shows the result of the above calculation.

![Figure 3: Wavefront error (mainly coma) coming from difference of the two liquids' thermal expansion coefficients. Triangles are experiments, dotted line corresponds to the simple 2D theory (section 2), closed circles corresponds to a 3D simulation.](image)

The figure 3 shows also several points which correspond to a 3D simulation on a geometry which corresponds exactly to the lens. One can observe a quite good agreement between experiments and the two theoretical methods for estimating the lens optical aberration. This enables to validate the simple model produced in section 2 as an accurate description of the aberrations of the lens produced by thermal effects.

4. **PHYSICAL LIMITATIONS TO THE SIZE OF LIQUID LENSES AND APPLICATION TO THE FIELD OF MINIATURE CAMERAS**

Using the above calculations and validation, one can build an application table, which makes possible to predict the size limitations that can be experienced with electrowetting liquid lenses, for a given application. There are 4 input parameters of such table:

1. clear pupil diameter (mm)
2. $\text{wfe}$ (in micrometers): assessed as the maximum wave front error (rms) of the coma aberration that can be tolerated in the application: this parameter should come out from ray-trace analysis of the whole optical system.
3. $\Delta T$: Total temperature range where the full lens quality is needed. (K or °C)
4. $\Delta c$: Optical power amplitude that is needed with varying the voltage ($\Delta c$ in dioptrees or m$^{-1}$)
Alternatively, one can choose not to specify the dioptic range, but rather the index difference between the two liquids. The figure 4 is showing the results. In order to be visual, one can plot a composite “merit parameter” of the lens which is given by $\Delta T/wfe$. The higher the merit parameter, the better optical quality of the lens for a given temperature range, or the larger the temperature range where the lens will have the full specification quality.

The practical use of this table is demonstrated on a given case: let’s suppose one wants to use the lens for an autofocus on a VGA miniature camera. The optical correction which is needed is the inverse of the nearest object distance. For an autofocus working with objects in the range 5cm-infinity, one should have at least $\Delta c=20$ dioptries. The temperature range for an outdoor application (mobile phone camera, camcorder etc…) would be at least -15°C to 50°C: $\Delta T=65K$. The maximum wavefront error which could be tolerated is of the order of 0.5µm. This means that the merit parameter of the lens should be at least $\Delta T/wfe = 130$. Considering the needed dioptic range, one can read from the table that the maximum lens diameter for this application would be of the order of 9mm, well above the existing lens diameters in this products.

The figure above is clearly dependent of the physical/chemical parameters considered (interfacial tension, etc…) and it is possible to optimize further the merit parameter of liquid lenses. The conclusion dawn here should not be considered as a hard wall, rather a state of the art of what could be achieved with liquid lenses at the moment.

5. CONCLUSION
In this paper we have been interested in describing the behaviour of a liquid lens based on electrowetting, when the two liquids have not the same densities. We could show that a simple model of a 2D calculation can describe quite well the wave front aberration induced by the liquid-liquid interface deformation. This was shown by comparing the 2D calculation against 3D simulations and also against experimental measurements. The results could be transcribed into an application chart which enables to assess the feasibility of a liquid lens, regarding a given application.

REFERENCES