Suppression of External Vibrations using an Electrowetting Lens

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***Abstract*— Axisymmetric resonance modes within an electrowetting lens are investigated. We demonstrate that both electrical modulation and external axial vibration will lead to axisymmetric Bessel modes in an electrowetting lens device. The effect of optical system vibrations are mitigated through use of an electrowetting lens.**

Keywords—electrowetting lens, vibration suppression, adaptive optics

I. Introduction

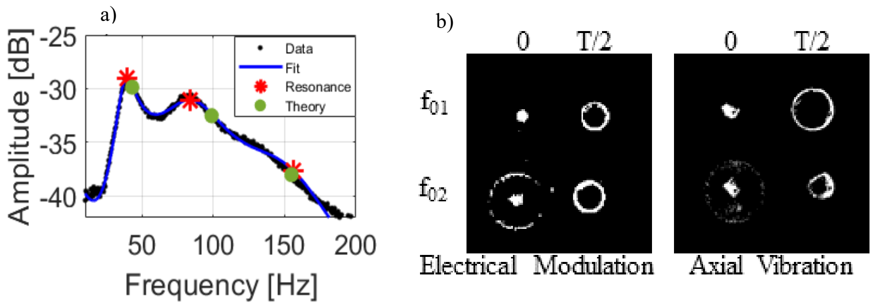
In the electrowetting-on-dielectric effect, an applied electric field is used to control the shape of a liquid droplet on a dielectric surface through an applied voltage [1]. Electrowetting optical devices have many attractive features. They are transmissive, compact, consume low electrical power, and are simple to fabricate. They are often implemented in the form of a cylindrical cavity which has functionalized sidewalls filled with two immiscible liquids where an applied voltage changes the curvature of the liquid-liquid interface. These devices have been implemented in applications ranging from microscopy to sensing [2,3]. There have been studies exploring the frequency response of electrowetting lenses to input voltage modulation [3-5] but the frequency response of an electrowetting lens subject to external vibration remained to be determined. We have studied the effect of external axial vibration and show axisymmetric Bessel modes are induced on the liquid-liquid interface. Finally, we present a method to mitigate the effect of optical system vibration by driving the electrowetting lens with an amplitude modulated signal.

II. Experimental Setup

Our electrowetting devices are constructed using a 4-mm inner diameter glass tube, which is coated with an electrode, a dielectric, and a hydrophobic coating [3]. To characterize the frequency response of the liquid-liquid interface, a collimated cw laser beam (635 nm) is passed through the device axis followed by a 10x objective, a 150-µm aperture and a photodiode. As the device is driven with an amplitude modulated signal, the resulting oscillations on the liquid-liquid interface along the optical axis are measured as changes in transmitted power spatially filtered through the pinhole onto the photodetector. We experimentally characterized the frequency response of the liquid-liquid interface by amplitude modulating the device driving signal with a random phase multi-sine ranging from 0.5 Hz to 200 Hz in steps of 0.5 Hz around a biased voltage of $70\ V_{rms}$, to create a flat liquid-liquid interface. The photodetector signal was recorded to determine the frequency response of our lens. Next, to confirm the presence of Bessel modes, the aperture and photodiode are replaced with a fast frame rate camera (500 fps) and the lens is either actuated electrically or is externally vibrated along its axis to induce liquid interface vibrations. For the external vibrations experiment, the optical system is placed on a shaker table and the electrowetting lens is actuated to create a flat liquid-liquid interface. External vibrations are generated on a shaker table and changes in transmitted power through the pinhole due to optical system vibration are measured.

III. Results

To locate the resonant peaks of the liquid-liquid interface, the steady-state response is analyzed using a fast Fourier transform (FFT). For electrical modulation, three resonant peaks are observable in the spectra as shown in Fig. 1(a). Reference [3] has developed a model predicting resonance frequencies as a result of electrical modulation in our devices, finding that resonance frequencies follow the roots of the zeroth order Bessel function of the first kind. The theoretical ratios of the Bessel modes are within 7.90 % of the experimental ratios, as shown in Fig. 1(a,c). Simulation results predict that resonances occur at the same frequencies regardless of electrical or mechanical forcing, however, the amplitude of liquid interfacial oscillation when density matched liquids are vibrated axially is predicted to be four orders of magnitude smaller than that induced by electrical forcing. This is due to the small Bond number, a unitless ratio of surface tension to body forces ($Bo = \frac{\Delta\rho \times g \times R^2}{\sigma}$). To enhance the interfacial oscillation, we intentionally chose a liquid system with a large density mismatch ($\Delta\rho = 250$ kg/m^3). Figure 1(b) shows that Bessel modes are induced on the liquid-liquid interface when subjected to axial vibration.



c)

	Resonance Frequency (Hz)			Bessel Ratios	
	1st	2nd	3rd	f_{02}/f_{01}	f_{03}/f_{01}
Theory	43	98.7	155	2.295	3.605
Experimental	39.5	83.5	156	2.114	3.949

Figure 1: (a) Frequency response of electrowetting lens to an amplitude modulated voltage input. The measured resonance frequencies are labeled with red stars. The theoretical predicted resonances are labeled with green dots. (b) Images of Bessel modes induced on the liquid-liquid interface: left, electrically, right mechanically. (c) Table including the first 3 resonant frequencies and Bessel ratios for theory and electrical modulation.

When using a combination of density matched liquids, the Bond number becomes much less than unity. Thus, the interfacial shape is dominated by surface tension and the electrowetting lens is robust to external vibration. A liquid combination of DI water and 1-Phenyl-1-cyclohexene (PCH), is used to mitigate the optical intensity variation of the transmitted beam caused by external vibration of optical components in the system. This is done by modulating the device driving electrical signal such that the optical response caused by amplitude modulation is π out of phase with the response caused by system vibration. As an example, the black line in Fig. 2 shows large intensity variation when the optical system is vibrated at 55 Hz. The intensity variation is attenuated by a factor of ~4 (blue line) when the electrical signal driving the device is modulated with a phase difference. The RMS value of normalized intensity variation is reduced from 0.5712 to 0.1142. Oscillations in the compensated waveform are attributed to lateral vibration induced in the system, not able to be compensated for using a lens device.

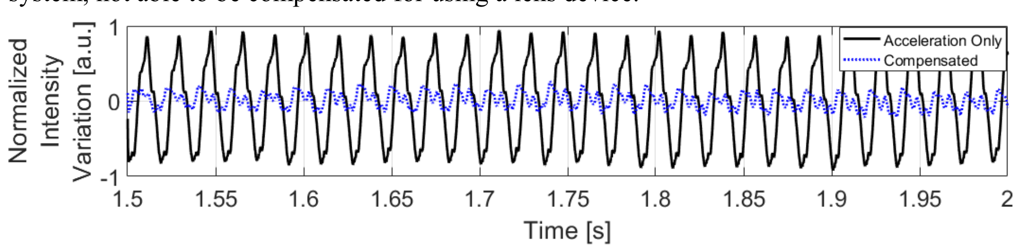


Figure 2: Steady-state response to axial vibration at 55 Hz. Black shows response to vibration only while blue shows the suppressed response by using an amplitude modulated lens driving signal. The RMS value of normalized intensity variation is reduced from 0.5712 to 0.1142. Oscillations in the compensated waveform are attributed to lateral vibration induced in the system, not able to be compensated for using a lens device.

IV. CONCLUSION

We have experimentally characterized the frequency response of the liquid-liquid interface in an electrowetting lens to drive input voltage modulation for frequencies ranging from 0.5-200 Hz. We show that Bessel modes are induced in an electrowetting lens subject to axial vibration. We have also demonstrated mitigation of the effect of externally induced axial vibration in an optical system by using input voltage modulation to the electrowetting lens.

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