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Acoustic Droplet Manipulation on Lubricant-Infused Surfaces

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Abstract

Both lubricant-infused surfaces and surface acoustic waves have been studied for their applicability to the field of microfluidics. However, combining the use of the two technologies has not been thoroughly explored. Specifically, this research aims to find an empirical relationship between the size of a droplet (characterized by its diameter) and the frequency required to induce motion. By placing droplets of various sizes on a lubricant-infused surface and testing the effects of surface acoustic waves of different frequencies, it has been determined that the frequency required to initiate movement of the droplet increases as the size of the droplet decreases. Experimental results indicate a logarithmic decaying relationship between frequency and droplet diameter, but more research needs to be done on droplets of diameters smaller than one millimeter. Even still, this research shows promise, as further developing an understanding of this relationship could allow greater control in microfluidic applications.

Introduction

This experiment involved the use of lubricant-infused surfaces (LIS) and surface acoustic wave (SAW) generating interdigital transducers (IDTs) for droplet manipulation purposes. Lubricant-infused surfaces consist of two main components: a porous underlayer of hydrophobic material (such as glaco, a polymer spray used to repel water from windshields), and a surface layer of oil [1]. The atomically flat surface provided by LIS allows for the placement and smooth movement of water droplets on the surface, as shown in Figure 1.

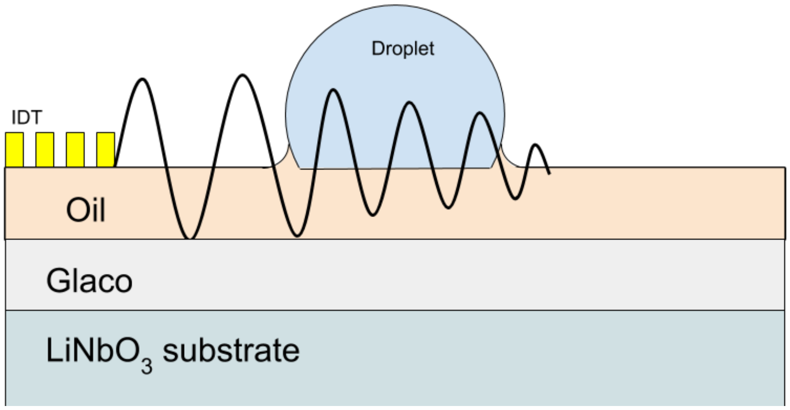

Figure 1: Schematic of a water droplet subject to surface acoustic waves on LIS. The sample consists of a layer of glaco deposited on a piezoelectric substrate, with a layer of oil infused. The droplet sits on top of the oil, affording a useful balance between contact area and low contact angle hysteresis and thus reducing the force needed from the IDT.

By condensing and then expelling droplets from the surface, the rate of heat transfer between the surface and the surrounding vapor can be increased. Because of their robustness, LIS have applications in industry and lab environments for controlled heat transfer, including using LIS to protect surfaces from unwanted biocontamination and fouling in heat exchangers [2].

SAW interdigital transducers are electrical devices used to generate surface acoustic waves of desired frequencies on piezoelectric substrates. Each IDT consists of a series of interspersed metal strips, the spacing of which determines the frequency of the surface acoustic wave generated. Many types exist for different applications, but for this research chirped IDTs were selected. Because of a differential spacing between fingers, they allow for operation over a broad range of frequencies rather than just one. As shown in Figure 1, the waves generated by an IDT propagate along the substrate perpendicular to the direction of the fingers. This directionality affords greater control over the effects of the waves.

When a surface acoustic wave encounters a droplet, the wave diffracts into the droplet, imparting its energy and momentum into the droplet [3]. A certain minimum force will have to be overcome in order to move the droplet. Otherwise the wave will simply induce acoustic streaming within the droplet without actually moving it. This minimum required force increases with the radius and also depends on the wettability of the droplet.

Procedure

Before any data could be collected, a lubricant-infused surface first needed to be fabricated on a piezoelectric $LiNbO_3$ substrate with a SAW IDT already fabricated on it. The fabrication of IDTs is a complicated process involving multiple days of work, and is not the main area of study for this project. As such, IDTs for this project have been supplied by a PHD student in Dr. Meacham's lab, Minyang Cui, who has been fabricating them along with IDTs for his own research to be efficient.

Once the IDT has been fabricated, I cleaned the sample using isopropyl alcohol and water. Then an even coat of glaco (a commercially available water repellant) was applied to the surface and allowed to dry. Once completely dry, the surface was spin coated with Krytox 104 oil (a medium viscosity industrial grade oil) for 60 seconds at 2000 RPM, thus creating a uniform oil layer on the $LiNbO_3$ substrate.

The substrate containing the IDT and LIS was then placed on a level stage. An LED screen was set up behind the stage for lighting, and an edgertronic SC1 high-speed camera with a 1x Nikon macro lens was fixed above the stage to record the effects of the surface acoustic waves on the droplets. The camera was calibrated by taking a picture of a syringe of known diameter once it was focused, allowing the size of one pixel in the shot to be calculated. The IDT was then supplied power from a function generator connected to an AC signal amplifier. This setup is shown in Figure 2.

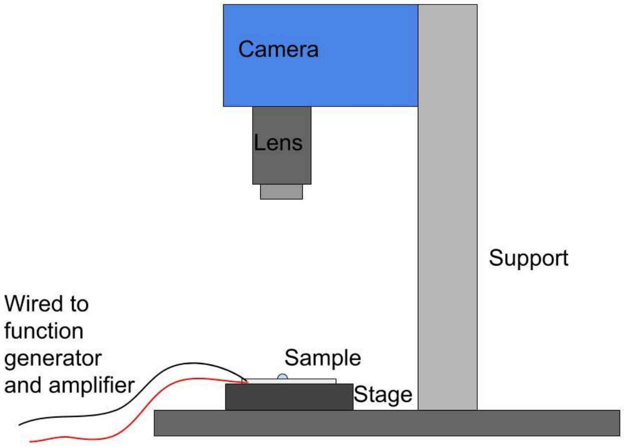

Figure 2: Experimental setup: The stage was leveled before conducting any experiments, to ensure that the effects of gravity would be negligible.

A droplet of deionized (DI) water was gently placed on the surface using either a 30 or 33 gauge syringe, depending on the desired droplet size. The function generator was set to a known frequency, and then turned on with the camera recording the results. A small amount of water was then added to the droplet, and the process was repeated until the droplet just began to slide over the surface. This trial signified the minimum size of droplet that would move with the known frequency and voltage parameters, so a note was made. Then the same process was repeated for different frequency and voltage conditions.

Results

Once data was gathered for a variety of frequencies, voltages, and droplet sizes, the video recordings were parsed into individual jpeg images and analyzed using ImageJ. The initial perimeter of each droplet was measured in ImageJ, and from this an equivalent diameter was calculated. It was observed that the droplets would begin to move only once a certain SAW frequency was reached. Once all of the images were processed, a graph of the threshold frequency versus droplet diameter was generated for analysis.

Shown in Figure 3 is a graph of the threshold frequency versus droplet diameter for a constant peak to peak voltages of 200mV and 150mV, respectively, supplied from the function generator. As can be seen, at both voltages a larger droplet diameter is correlated with a lower threshold frequency. At 200mV, it appears that the threshold frequency increases more quickly as the droplet size gets smaller.

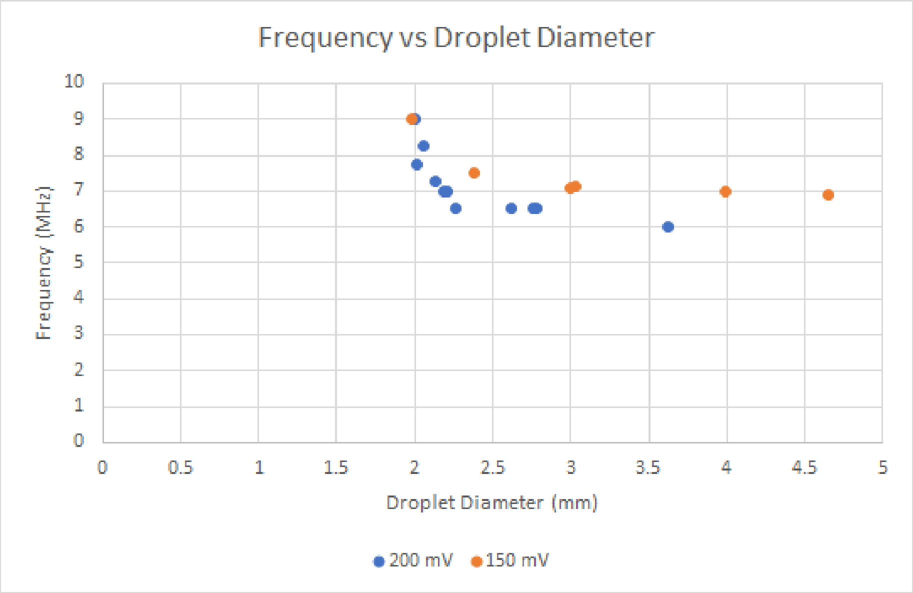

Figure 3: Threshold frequency for onset of droplet movement *vs.* droplet diameter for 150mV and 200mV actuation frequencies.

It should be noted that trials were done with droplets smaller than 2mm, but these results were largely inconclusive and are hence not included in Figure 3. These smaller droplets were able to move with frequencies between 8 and 10MHz, but the relationship between droplet diameter and threshold frequency was not clear.

For each data set, an empirical relationship between the threshold frequency and droplet diameter was found by shifting the diameter data to the left by a constant and then applying a logarithmic fit using Microsoft Excel. This fitting process is shown in Figure 4 for the 200mV trials.

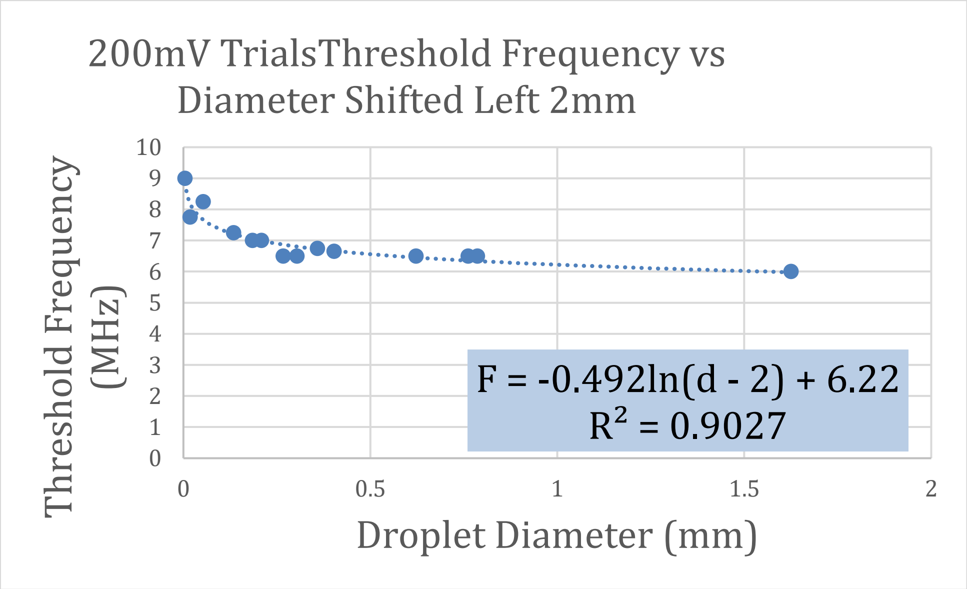

Figure 4: Threshold frequency for onset of droplet movement *vs.* droplet diameter for an actuation frequency of 200mV, shifted left by 2mm in order to find a fit equation with R^2 of 0.9027.

The relation derived from this method is

$$F = -0.492 ln(d - 2) + 6.22 \qquad \text{Eq. 1}$$

where F is the threshold frequency in MHz and d is the droplet diameter in mm. The same methods were applied to the data for the 150mV, and the following relation was found, with the same units as above.

$$F = -1.407 ln(d - 1) + 8.40 \qquad \text{Eq. 2}$$

Discussion

From these results, it is clear that there is an inverse relationship between the droplet size and the threshold SAW frequency needed to get the droplet to move on LIS. The relations described above predict the behavior of the droplets well for the larger droplet sizes, but fail to account for the behavior of smaller droplets. It is possible that with the smaller droplet sizes, the method of depositing the droplet onto the surface began to play a larger role in the dynamics of the droplet movement, as adding water to a small droplet seems to affect its contact angle more than for larger droplets. Also, smaller droplets tend to stick more to even a 33 gauge needle, so the very act of depositing the droplets will disturb their surface. So small droplets deposited in slightly different ways could experience different contact areas, and thus not interact the same way with SAW of the same frequency. This effect could be alleviated in future research by condensing droplets onto the substrate, as this would ensure they all form in a uniform manner.

One possible explanation for the inverse relationship between frequency and droplet size is that the smaller droplets have a higher resonant frequency. In general, I expect it to be easier to transmit momentum into droplets at their resonant frequency, hence shifting the threshold frequency to higher values for these smaller droplets.

The use of LIS for heat transfer purposes is a major area of research already, as is the use of SAW IDTs for droplet manipulation purposes. However, the intersection between the two fields of study warrants more research. The effects of SAW IDTs for droplet manipulation have been analyzed on various types of lubricant-infused surfaces manufactured in different ways and containing lubricants of various viscosities [3]. However, a relationship between droplet size and the threshold frequency to induce movement had not yet been studied. This relationship is worth finding, because it would potentially allow droplets of certain sizes to be manipulated while leaving droplets of other sizes in place. A method like this could see use in heat transfer applications, as the larger droplets that are occupying nucleation sites could be targeted and removed, making room for more droplets to form. This would increase the rate of droplet nucleation and thereby the rate of heat transfer between the surface and surrounding air. A relationship between droplet size and threshold frequency could also be useful for more typical microfluidic applications involving the movement and mixing of individual droplets.

Conclusion

In short, it has been shown that the threshold frequency to move a droplet using surface acoustic waves on a lubricant-infused surface increases as the diameter of the droplet decreases. An empirical relationship between these two quantities has been found, however more research is needed to experiment more precisely with smaller droplet sizes, as well as to quantify the potential heat transfer benefits of such technology and methods.

References

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