Study of Piezoelectric Transducer for Liquid Ejection

S. F. Hon, K. W. Kwok
Department of Applied Physics
The Hong Kong Polytechnic University
Hong Kong, China
07900570r@polyu.edu.hk

***Abstract*— Self-focused acoustic transducers using using Fresnel zone plates have been fabricated and used to eject droplets of high-viscosity liquid, without nozzle, in the drop-on-demand mode. The Fresnel zone plate consists of a series of annular electrodes of half-wave-band source, and the acoustic waves are focused by constructive wave interference. Droplets of glycerin with a high-viscosity of 1400 cP can be ejected under a field of 200 kV/m and at a repetitive frequency of 120 Hz. The acoustic pressure distribution in the glycerin has been been simulated using an open-source computational fluid dynamic code OpenFOAM and measured using a needle-type hydrophone. Both the simulation and measurement give the location of two focal points which agree with the observations in the droplet ejection experiment.**

I. INTRODUCTION

Various droplet ejection mechanisms have been developed and employed for ink-jet printers to realize high resolution, fast, and reliable printing at low cost; these include piezoelectric actuation, thermal bubbles, thermal diaphragm vibration, electrostatic actuation, and acoustic waves. Recently, the developed technologies have been studied for and found potential in other applications, such as DNA spotting, drug delivery, cell sorting, fuel injection, and microjet propulsion. However, most of the methods eject ink droplets through a small nozzle which is difficult to construct with good uniformity, and susceptible to clogging. Therefore, nozzleless ejection is desired, in particular for applications involving biological/chemical precipitates and volatile solvents.

Focused acoustic beam has been shown to be capable of ejecting liquid droplets from the surface of the liquid, without any nozzle. A variety of acoustic focusing mechanisms have been reported. The straightforward approach is to use a spherical acoustic lens or a Fresnel lens to focus the acoustic beam. However, the fabrication of the acoustic lenses by mechanical grinding and polishing is difficult and expensive. Self-focused acoustic transducers based on Fresnel zone plates, which were originally developed for focusing electromagnetic waves, has been demonstrated to efficiently eject liquid droplets. The zone plate consists of a series of annular electrodes of half-wave-band source, and the beam is focused at the liquid surface by constructive wave interference [1]. In general, liquid droplets can be ejected in the drop-on-demand mode, and the size, which is primarily determined by the wavelength of the acoustic beam, can be as small as 10 µm. However, most of the work are focused on ejecting low-viscosity liquids, such as water (1 cP) [1-3], photoresist (5 - 100 cP) [45] and silicone resin (~400 cP) [5]. In this paper, we report the nozzleless droplet ejection of glycerin (1400 cP) using a self-focused acoustic transducer with a Fresnel zone plate. The distribution of pressure (change) generated by the transducers in the liquid have been simulated and compared with the experimental results.

II. DESIGN AND SIMULATION

Fresnel zone plate

Figure 1 shows the annular electrodes of half-wave-band source patterned on the Fresnel zone plate. Acoustic waves are generated at the annular electrodes and propagate towards the designed focal point F_d. In order to realize the self-focusing effect and enhancement in pressure intensity, all the waves when arrive at F_d should be in-phase and constructively interfere with each other. The wave generated at a particular point of an annular electrode should have a path difference of an integral number of wavelength from the wave generated at a corresponding point of a adjacent electrode (Fig. 2):

$$R_{i+2} - R_i = m\lambda \qquad [1]$$

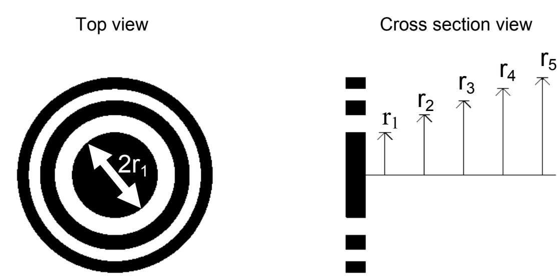
where m is an integer and λ is the acoustic wavelength in liquid. Destructive interference between the waves generated at the same annular electrode should be minimized. Hence, the path difference between the waves generated at the edges of an annular electrode should satisfy (Fig. 2):

$$R_{i+1} - R_i = \lambda/2 \qquad [2]$$

In order to fulfill both the conditions (Eq. 1 and 2), m is taken as 1. The radii r_n of the annular electrodes (Fig. 1) are then calculated as:

$$r_n = n\lambda f_d + n^2\lambda^2/4 \qquad [3]$$

where n = 1, 2, 3 ….and f_d is the focal length.



.

Figure 1. The annular electrodes of Fresnel half-wave-band source patterned to focus the acoustic wave

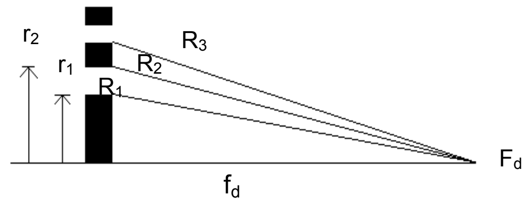


Figure 2. Effect of propagation path difference on wave interference with Fresnel half wave source.

Focused Acoustic Transducer

In this work, PZT plates of thickness 0.5 mm are used to fabricate the Fresnel zone plates for the self-focused acoustic transducers. The resonance frequency of the PZT plate is about 4.28 MHz. The radii of the annular electrodes are calculated using an acoustic wavelength of 448.6 μm and a designed focal length of 10 mm by Eq. 1. The acoustic wavelength is calculated using a wave velocity of 1920 m/s for glycerin and an operating frequency of 4.28 MHz. Including the central electrode, six annular electrodes are used for the present work. The diameter of the outmost annular electrode is 14.89 mm. The annular electrodes are patterned on the PZT plate using the standard photolithography technique. The PZT plate is then mounted on the top of a cylindrical metal holder (with an inner diameter of 17.5 mm) as shown in Figure 3. The holder is shielded by a thin metal plate with a hole of diameter 1.0 mm in the center to form the transducer.

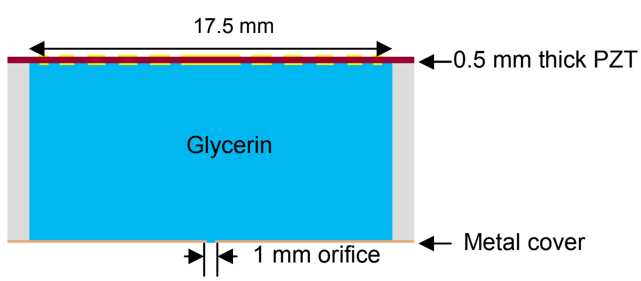


Figure 3. Schematic diagram of the focused acoustic transducer.

OpenFOAM Simulation

Several theoretical models have been suggested for studying the pressure profile generated by the focused acoustic transducers. Huang et al. suggested a simplified reflection model which takes into account the acoustic loss in the liquid and the two-time wave reflections at the water-air and water-transducer interfaces [1]. In the model suggested by Elrod et al., the intensity of the incident acoustic wave and the speed of sound in the liquid are considered, and the radiation pressure is evaluated from the Langevin radiation pressure [6,7]. Radiation pressure associated to the acoustic wave is defined as the mean of energy density of the acoustic wave at the surface of liquid. If the pressure is larger than the surface tension of the fluid, the droplet is expelled from the surface. [6] However, both models provided only a surface deformation of fluid due to the particle displacement.

In this work, OpenFOAM is used to calculate the pressure distribution and hence to locate the focal point in the liquid. OpenFOAM is a finite volume method of Computational Fluid Dynamics tools [8]. It defines a mesh of arbitrary polyhedral cells in 3D, bounded by arbitrary polygonal faces, and hence can calculate the pressure distribution inside the liquid.

The geometry of the transducer (Fig. 3), including the annular electrodes and transducer holder, are used for the simulation. As it is aimed to locate the focal point resulted from the constructive wave interference, the thin metal cover is not included in the simulation, and the liquid depth (30 mm) is set to be larger than the designed focal length (10 mm) so as to eliminate the effect of wave reflection. The region covered by the annular electrodes is meshed and defined as a moving wall with a uniform displacement (for generating the ultrasonic waves), while the rest of the Fresnel zone plate is defined as a fixed wall. The transducer hold is defined as Neumann boundary, at which the gradient of pressure is equal to zero, to reduce the effect of wave reflection. A density of 1.26 g/cm^3, a viscosity of 1400 cP and a wave velocity of 1920 m/s are used for glycerin in the simulation. SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm established by Patankar and Spalding for Pressure-Velocity Coupling is adapted to calculate the pressure change as a function of time in the liquid.

III. Results and Discussion

OpenFOAM Simulation

Figure 4 shows the simulated pressure distribution in the glycerin at t = 7.00935 µs (i.e. 7.00935 µs after the electroded region starts to vibrate outwards from stationary). It can be seen that the acoustic waves are focused effectively, giving a much stronger pressure near the zone plate and along the axial direction. The variation of pressure along the axial direction (i.e. MN in Fig. 4) at t = 7.00935 µs is shown in Figure 5, while the variation of pressure with time at different positions along the axial direction is shown in Figure 6. Because of the piezoelectric effect of the PZT plate, the electroded region vibrates continuously and sinusoidally. As a result, the pressure at each position also varies with time sinusoidally (Fig. 6). Nevertheless, the pressure distributions at different times are similar, still having a much larger pressure value at distances shorter than 8 mm.

In order to locate the focal point, the pressure amplitude at each position along the axial direction (i.e. MN in Fig. 4) is determined, giving the results shown in Figure 7. Similarly, the pressure amplitude has a large value only at distances shorter than 8 mm. A sharp focal point (F_0) at which the pressure amplitude reaches a maximum value is clearly observed at a distance of 2.44 mm (f_0) from the Fresnel zone plate. Although it has been shown that the observed focal length for the Fresnel zone plate is usually smaller than the designed one calculated by Eq. 3 [9-10], the difference is not as large as the one observed in our simulation (2.44 mm versus 10 mm). As shown in Figure 7, there is another focal point (F_1) barely observed at a distance of 6.18 mm (f_1), which is most likely equivalent to the one usually reported by the other work [9-10]. Figure 8 shows the variations of the pressure amplitude normal to the axial direction at a distance of f_0 and f_1 (i.e. OP and QR in Fig. 4). The pressure amplitude decreases drastically from the central of the plate, indicating that the acoustic wave is effectively focused and the corresponding focused point is very small at 3.0 mm. It is also seen that the pressure amplitude varies quite sinusoidally along the axial direction as shown in the inset of Figure 7. The "period" for the variation is about half of the acoustic wavelength in glycerin (448 μm). This should be attributed to the constructive interference between the waves generated at different positions of the annular electrodes.

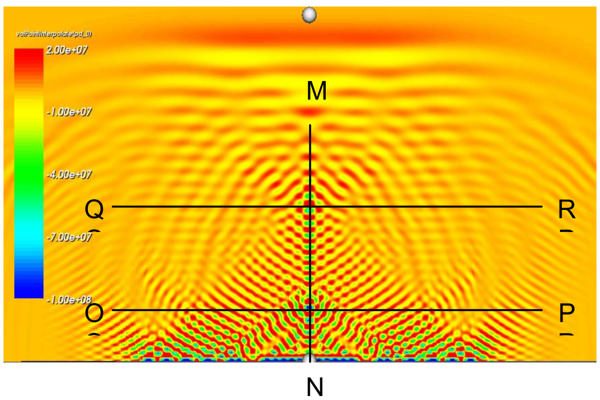


Figure 4. Simulation pressure distribution in glycerin at t = 7.00935μs.

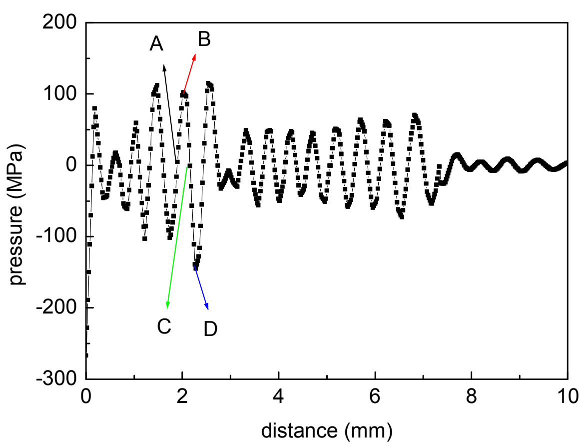


Figure 5. Variation of pressure along the axial direction (i.e. mn in Fig. 4) at t =7.00935 μs .

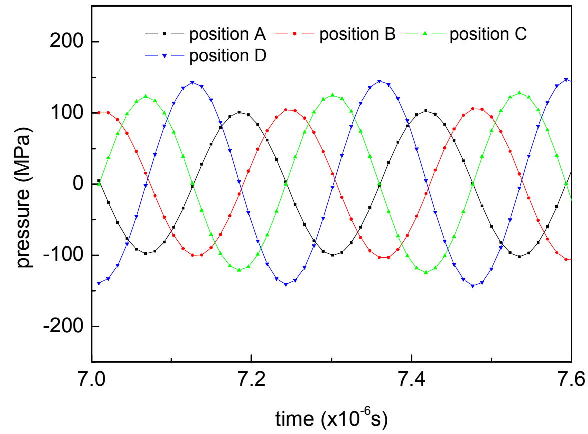


Figure 6. Variation of pressure with time at different positions along the axial direction (refer to Fig. 5).

Measurement of the Pressure Distribution

A needle-type hydrophone was used to study the pressure distribution of the acoustic waves in the glycerin generated by the focused acoustic transducer. The active element of the hydrophone is a poled P(VDF-FrFE) copolymer film with a diameter of 0.5 mm and a thickness of 6 μm [11]. The voltage generated by the hydrophone is linearly dependent on the pressure of the wave incident on it, so the distribution of the pressure can be determined. Figures 9 and 10 show the variations of the observed voltage along and normal to the axial direction, respectively. Two focal points are observed at a distance of 2.36 mm and 6.18 mm, respectively (Fig. 9), which agree with the simulation results as shown in Figure 7. As the active element is large, about 0.5 mm in diameter, the measurement only gives the averaged pressure at the position. As a result, the measurements cannot show a sharp focal point at F_0 and F_1. It is also noted that, although the measurement show the variation of pressure along the axial direction (Fig. 9), the observed "period" of the variation is about two times of the simulation results (Fig. 7).

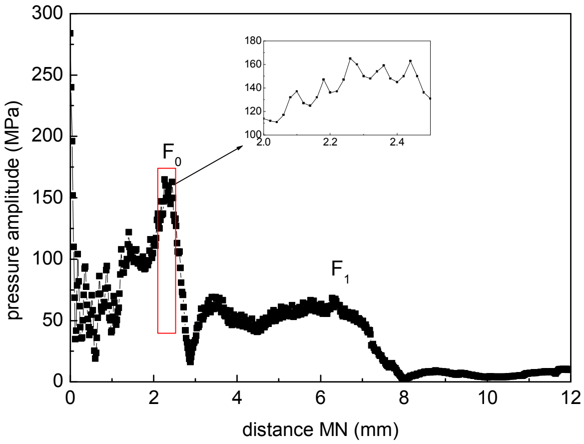


Figure 7. Variation of pressure amplitude from the simulation along the axial direction

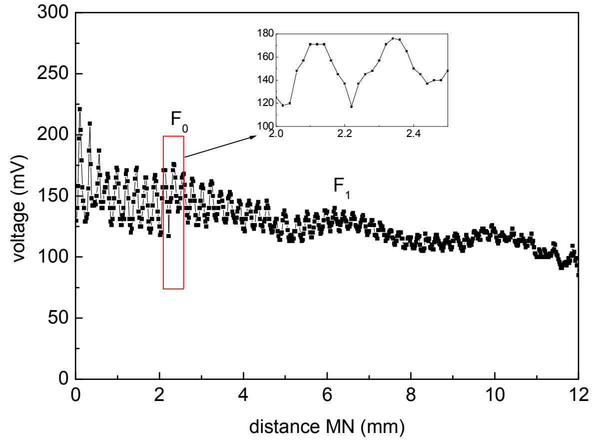


Figure 9. Variation of voltage measured by the hydrophone along the axial direction.

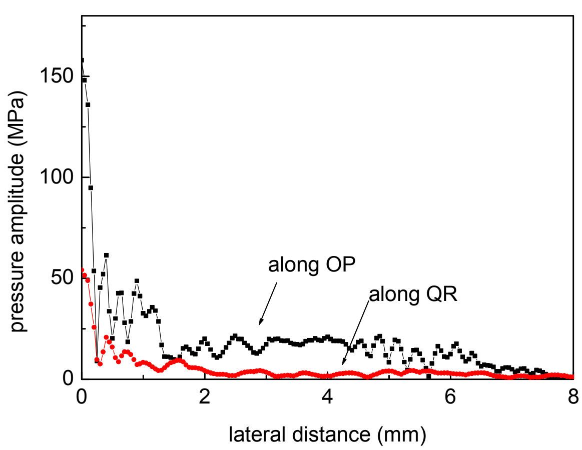


Figure 8. Variation of pressure ampliude normal to the axial direction a distance of f_o and f_1.

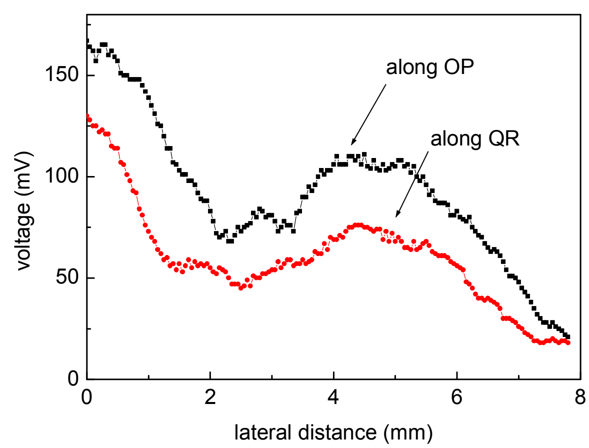


Figure 10. Variation of the voltage measured by the hydrophone normal to the axial direction at a distance of f_0 and f_1.

Ejection of glycerin droplets

Glycerin droplets have been successfully ejected using the focused acoustic transducer. The transducer was driven by a short wave train at an operation frequency of 4.28 MHz. The depth of the glycerin was adjusted until the droplets could be ejected from the 1-mm orifice (Fig. 3). Figure 11 shows the ejection of the droplets at a repetition frequency of 120 Hz. It has been shown that glycerin droplets can only be ejected at a liquid depth of 2.5 and 6.2 mm, respectively, which agree with both the simulated and observed focal length f_0 and f_1 (Figs. 7 and 9). The voltage and duration of the wave train for ejecting the droplets at f_0 are about 100 V and 3 ms respectively, both are smaller than those used for ejecting the droplets at f_1. These also agree with the simulation and experimental results, both showing a larger pressure at f_0 than at f_1.

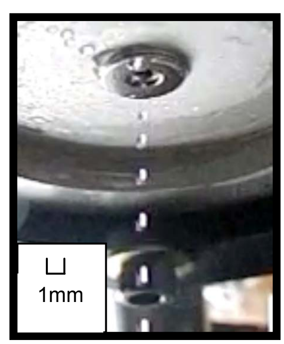


Figure 11. Glycerine droplet ejected from the focused acoustic transducer

IV. CONCLUSION

High-viscosity glycerin droplets have been successfully ejected, without nozzle, by a self-focused acoustic transducer. The focused transducer is fabricated using a Fresnel zone plate, which consists of a series of annular electrodes of half-wave-band source. The acoustic waves are focused by constructive wave interference. The acoustic pressure distribution in the glycerin has also been studied by simulation using OpenFOAM and measurement using a needle-type hydrophone. Both the simulation and measurement determine similar locations of two focal points, which agree well with the observations in the droplet ejection experiment

ACKNOWLEDGMENTS

This work was supported by the Research Committee and the Centre for Smart Materials of The Hong Kong Polytechnic University.

REFERENCES

[1] Dai Huang, Eun Sok Kim, "Micromachined acoustic wave liquid", Journal of microelectronical system, vol. 10, no. 3, 2001.

[2] Hongyu Yu, Jae Wan Kwon, Eun Sok Kim, "Microfluidic mixer and transporter based self focusing acoustic transducer", Journal of microelectrimechanical system, vol. 15, no. 4, 2006.

[3] Hongyu Yu, Jae Wan Kwon, Eun Sok Kim, "Chembio extraction on chip by nanoliter droplet ejection", Lab Chip, 2005, 5, 344-349.

[4] Utkan Demirci, "Acoustic Picoliter Droplets for Emerging Applications in Semiconductor Inducstry and Biotechnology", Journal of microelectronical system, vol. 15, no. 4, 2006

[5] Isao Amemiya, Yuko Nomura, Kenichi Mori, "LED Packaging by Ink-jet Microdepostion of high-viscosity Resin and Phosphor" SID 07 Digest, pp. 1603-1606

[6] S. A. Elrod, B. Hadimloglu, Khuri-Yakub, "Nozzleless droplet formation with focused acoustic beams", J. Appl. Phys. 65(9), May 1989.

[7] C. Cinbis, N. N. Mansour, B.T. Khuri-Yakub, " Effect of surface tension on the acoustic radiation pressure- induced motion of the water-air interface" , Journal of Acoustic Society of America, 94(4), 1993

[8] Hrvoje Jasak, "Error analysis and Extimation for the Finite Volume Method with applications to fluid flows" thesis for Imperial College of Science, Technology and Medicine, pp. 64-72, 1996

[9] M. Z. Sleva and W. D. Hunt, "Design and construction of a PVDF Fresnel lens" 1990 Ultrasonic symposium, pp 821-827

[10] Schindel, D.W., Bashford, A.G., Hutchins, D.A. "Focussing of ultrasonic waves in air using a micromachined Fresnel zone-plate", 1997 Ultrasonics 35 (4), pp. 275-285 6

[11] Sien Ting Lau, "acoustic sensors using 0-3 nanocomposites", thesis for Hong Kong polytechnic University, pp. 86-120, 2001