Ejection Characteristics and Drop Modulation of Acoustic Inkjet Printing Using Fresnel Lens*

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Abstract
Acoustic Inkjet Printing uses an acoustic beam focused on a free liquid surface for drop ejection. This method can eject small drops without precise nozzle fabrication in comparison with thermal inkjet and piezoelectric inkjet. The fresnel lens was selected for focusing acoustic waves because of the precise and easy manufacturing by LSI process. The actual devise was made from a Si substrate and characteristics of its drop ejection were investigated. Furthermore, sound field by fresnel lens was calculated using Rayleigh’s Equation to be compared with the experimental results that showed good agreement. Finally it was proved that acoustic inkjet printing with fresnel lens is suitable for drop modulation by utilizing second harmonic focus.

Key words: Sound Field Control, Acoustic, Ultrasonic Wave, Inkjet Printer, Drop Ejection, Fresnel Lens, Drop Modulation, Rayleigh’s Equation

1. Introduction
It is known that when a underwater ultrasonic wave is focused on a free liquid surface, liquid drop is ejected from the liquid surface by its radiation pressure (1), and it is reported that the acoustic inkjet printing was devised by applying this phenomenon (2), and that the number and size of drops ejected can be controlled by utilizing tone burst ultrasonic wave (3). This method can eject small drops in comparison with the thermal method and piezoelectric method that are currently in popular use, and does not need a nozzle with a small aperture that causes clogging because it can eject drops from a free ink surface. This method is regarded with high expectations in terms of image quality enhancement and reliability (4).

Spherical transducers, spherical lens, fresnel lens, phased array lens, etc. exist as a means to focus ultrasonic waves. However, the multi-faceted fresnel lens, which can be manufactured with precision by LSI process, has been selected because they are required to be arranged densely in the acoustic inkjet head (5).

This report describes the test results of acoustic inkjet with fresnel lens in which a single lens head for basic experiment and an array lens head on which multiple lenses are arranged to be used for actual printers were designed and test-manufactured, and their drop ejection characteristics were evaluated. In addition, when the size of drop is reduced to aim for high-resolution image quality in low density areas, a problem arises in where many drops are necessary in high density areas, which reduces print speed. In order to simultaneously achieve high-resolution image quality and high print speed, drop modulation that changes drop size according on image density will become an effective technology.
Accordingly, we studied the possibility of drop modulation using a focus by intervention of a second harmonic wave in acoustic inkjet with fresnel lens.

In the meantime, drop ejection characteristics of acoustic inkjet largely depend on the sound field formed in a liquid by ultrasonic wave radiated from the lens. The sound field is expressed by Rayleigh's Equation that is the form of a surface integral \(^6\), but some methods are proposed in which this equation is converted into a line integral to calculate a sound field \(^7\) \(^8\) \(^9\). However, these concern to flat or concave transducers, and therefore, in this report, the Rayleigh Equation was numerically integrated while being kept as a surface integral to calculate a radiated sound field by fresnel lens and the results of the calculation was compared with the experimental results.

2. Nomenclature

\[ A : \text{Vibration amplitude of lens surface [m]} \]
\[ d_i : \text{Height of each phase ring [m]} \]
\[ dS : \text{Area element of lens surface [m}^2\text{]} \]
\[ F : \text{F value of lens} \]
\[ f : \text{Burst frequency [Hz]} \]
\[ f_d : \text{Designed burst frequency [Hz]} \]
\[ k_l : \text{Wavenumber in liquid [rad/m]} \]
\[ k_s : \text{Wavenumber in lens [rad/m]} \]
\[ l_d : \text{Designed focal distance [m]} \]
\[ p : \text{Sound pressure [Pa]} \]
\[ p_N : \text{Normalized sound pressure} \]
\[ p_0 : \text{Sound pressure at lens bottom is } d_0 = 0 \text{ [Pa]} \]
\[ R : \text{Coordinate in radial direction [m]} \]
\[ R_n : \text{Radius of each ring [m]} \]
\[ r : \text{Distance between area element of lens surface and observation point [m]} \]
\[ S_T : \text{Area of lens surface [m}^2\text{]} \]
\[ t : \text{Time [sec]} \]
\[ v_T : \text{Vibration velocity of lens surface [m/sec]} \]
\[ V_l : \text{Sound velocity in liquid [m/sec]} \]
\[ V_s : \text{Sound velocity in lens [m/sec]} \]
\[ Z : \text{Coordinate in sound axial direction [m]} \]
\[ \alpha : \text{Ultrasonic wave absorption coefficient [neper/m]} \]
\[ \lambda_l : \text{Wavelength in liquid [m]} \]
\[ \lambda_s : \text{Wavelength in lens [m]} \]
\[ \rho_l : \text{Liquid density [kg/m}^3\text{]} \]
\[ \omega : \text{Vibration angular velocity of lens surface [rad/sec]} \]

3. Experimental Apparatus and Method

3.1 Head Structure

Two types of heads for acoustic inkjet printing were used in the experiment. One is the single lens head on which only one lens is formed, and the other is the array lens head on which multiple lenses are arranged. The single lens head, which was scaled up to for basic experiment, has a bigger lens diameter and focal distance. The array lens head is for printers and has a plate with apertures to maintain a free liquid surface.

Figure 1 shows a cross section of the head. On one side of the 550\(\mu\)m-thick Si substrate, a fresnel lens is formed by RIE (Reactive Ion Etching), and on the other side, a
transducer is formed by a 20µm-thick ZnO by the sputtering method, sandwiched between electrodes. Ultrasonic waves generated by the transducer propagates through the Si substrate, radiates from the fresnel lens into the liquid, and is focused on the liquid surface.

3.2 Fresnel Lens Design
A four-phase fresnel lens is used for the balance of focus efficiency and manufacturing precision. Figure 2 shows the coordinate axes and symbols concerning each ring. For coordinates, using the cylindrical coordinate system where the origin is at the bottom of the lens center, “R” is the radial direction and “Z” for the direction of the sound pressure conveyance. After the designed burst frequency $f_d$ and designed focal distance $l_d$ are determined, the height of each phase ring $d_i$ and the radius of each ring $R_n$ are designed based on the equation (1) and (2) that show a relation between geometrical path distance and phase lag. In continuance, lens diameter is determined from the designed focal distance $l_d$ and $F$ value of lens. For this event, five types of lenses shown in Table 1 were designed and fabricated for use in the experiment. The equation (1) and (2) prove that on the same lens, a focus can be obtained at the designed focal distance $l_d$ even by the second harmonic wave whose wavelength is one-half.

$$d_i = \frac{i}{4} \frac{1}{\lambda_i} - 1/\lambda_i \quad \text{(i = 0, 1, 2, 3)} \quad (1)$$

$$R_n^2 = \left(l_d - d_i + n \frac{\lambda_i}{4}\right)^2 - \left(l_d - d_i\right)^2 \quad \text{(n = 1, 2, 3, \ldots \ldots \ldots)} \quad (2)$$

3.3 Experiment Equipment
Figure 3 shows the observation equipment for the ejected drop. RF burst waveform generated by the pulse generator and signal generator is amplified by the RF amplifier and supplied to the transducer of the head. In addition, a signal synchronized with RF burst waveform is sent to the LED to observe drop by

![Fig.2 Fresnel Lens Cross Section](image)

![Table1 Parameters of Designed Lenses](image)

![Fig.3 Experimental Drop Observation System](image)
synchronized image. When a single lens head is used, a pool filled with liquid is set above
the lens of the head. The liquid surface level is controlled by adjusting the level of the
liquid tank connected to the pool while measuring the surface level with a laser
displacement meter. When an array lens head is used, the liquid tank is connected with the
head and the liquid surface level is fixed because the aperture of the plate maintains the
liquid surface.

4. Calculation Method of Sound Field

If uniform plane wave propagates in the Si substrate, the vibration velocity of lens
surface of each phase in the fresnel lens is $v_T = A \exp\left( j\omega (t - d_i / V_s) \right)$, and when
Rayleigh Equation (6) is applied to the fresnel lens, equation (3) is obtained.

In equation (3), normalizing sound pressure $p$ by $p_0 = \rho_0 V_l A \exp(j\omega t)$ which is sound
pressure at lens bottom ($d_0 = 0$) and considering absorption of ultrasonic wave in liquid (8),
equation (4) which expresses normalized sound pressure $p_N$ is obtained. $e^{-\alpha r}$ in
equation (4) is the effect of absorption.

In equation (4), dividing lens surface $S_T$ and integrating numerically, sound pressure
distribution in liquid is obtained.

Table 2 shows absorption coefficients and sound velocities of water, ethanol, and IPA
(10), and Figure 4 shows dependency of absorption coefficient on burst frequency. In
Figure 4, absorption coefficients of water, ethanol, and IPA are widely different. It is the
reason why they were selected for calculation and experiment.

$$p = \rho_0 \int_{S_T} v_T \left( t - \frac{r}{V_j} - \frac{d_i}{V_s} \right) \frac{dS}{2\pi r}$$

$$p_N = jk \int_{S_T} e^{-jk\rho} e^{-\eta\rho} e^{-\alpha r} \frac{dS}{2\pi r}$$

Table 2 Absorption Coefficient and Sound Velocity at 20 degree C

<table>
<thead>
<tr>
<th></th>
<th>$\alpha \rho''$ [neper/(m$\cdot$Hz$^2$)]</th>
<th>$V_l$ [m/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>$2.6 \times 10^{-14}$</td>
<td>1482</td>
</tr>
<tr>
<td>Ethanol</td>
<td>$5.2 \times 10^{-14}$</td>
<td>1182</td>
</tr>
<tr>
<td>IPA</td>
<td>$9.2 \times 10^{-14}$</td>
<td>1170</td>
</tr>
</tbody>
</table>

Fig.4 Dependency of absorption Coefficient on Burst Frequency
5. Results and Discussion

5.1 Example of Sound Field Calculation Result

The sound field calculation results, in combination of Lens No.3 and water, are shown in Figure 5 and 6. Figure 5 shows sound pressure distribution on the Z axis, and Figure 6 shows sound pressure distribution on the focal plane.

As shown in Figure 5, according to calculation, the focal distance and sound pressure at focus changes according to the burst frequency. Peaks appear on the Z axis, which shows that focuses by the fundamental wave and second harmonic wave exist. In Figure 6, the calculated focus size on each focal plane is shown.

Hereafter, the focuses by the fundamental wave and second harmonic are referred to as 1st focus and 2nd focus, respectively, and explained in detail in the next section.

5.2 Focal Distance

The calculated focal distance and the experimental liquid surface level at which a drop can be ejected were compared using the burst frequency as a parameter. In the experiment, the amplitude and duration of RF burst waveform applied to the transducer were fixed to keep the applied energy constant, and the range of the liquid surface level at which a drop can be ejected was measured. Figure 7-1, 7-2, and 7-3 show the results in combination of Lens No.2 and water, Lens No.3 and water, and Lens No.3 and ethanol, respectively.

The calculated focal distance and the experimental liquid surface level at which a drop can be ejected changes linearly against the burst frequency, and each value shows a good match. In addition, there are the second calculated values and experimental values on the higher frequency side, and when they are compared with the values at the same focal distance, their frequencies are two times higher than those of the 1st focus, which indicates that they are the 2nd foci by the second harmonic wave.

The figures show that focal distance becomes longer as
ultrasonic frequency becomes higher, and it also longer in ethanol whose sound velocity is slower than water. This can be speculated from the fact that in equation (2), when lens size is fixed, $l_d - d_i$, which is equivalent to focal distance, becomes bigger as the wavelength on the right side becomes bigger. In addition, it can be predicted that when lens size is fixed, the focusing state deviates from the ideal state and focusing efficiency deteriorates as the applied burst frequency $f$ deviates from the designed burst frequency $f_d$, which reduces sound pressure at focus. Therefore, it is thought that the 1st focus by the fundamental wave and the 2nd focus by the second harmonic wave exist in different frequency ranges.

In the experiment, periodic change of focal depth was also observed according to burst frequency changes. The cycle was about 7.7MHz regardless of lens type. This is in agreement with frequency spacing at which the integral multiplication of half wavelength matches the 550µm-thick Si substrate used in the experiment, and therefore, it is thought to be the influence of ultrasonic wave transmittance based on resonance in the substrate layer

5.3 Sound Pressure at Focus and Energy Threshold

The threshold of applied energy when a drop can be ejected is thought to depend on the factors such as sound pressure at focus, kinetic energy of ejected drop, and surface tension at the air-liquid interface. Here, based on the thought that sound pressure at focus is the dominant factor, the calculated normalized sound pressure at focus and the experimental energy threshold of drop ejection are compared while ignoring other influences. It is thought that the higher the calculated normalized sound pressure at focus is, the focusing...
efficiency increases and the applied energy to the transducer necessary for drop ejection decreases in the experiment, and therefore, the energy threshold is expected to be low. The threshold of the applied energy in this experiment is defined as the shortest burst length at which a drop can be separated from the liquid surface when the amplitude of RF burst waveform is fixed.

First, Figure 8 shows the calculation results when absorption of ultrasonic wave is considered and when it is ignored in combination of Lens No.3 and water. When absorption is ignored, frequencies at which the 1st focus and 2nd focus become maximum almost coincides with the designed burst frequency of $f_d = 133\text{MHz}$, and the second harmonic wave of 266MHz, respectively. This is because focusing efficiency of lens can be interpreted as being maximized at the designed burst frequency $f_d$ and its second harmonic wave. However, when absorption is considered, the frequencies of the 1st focus and 2nd focus that become maximum is lower in comparison to when absorption is ignored and the sound pressure at focus itself is also lower.

Next, Figure 9-1 and 9-2 show the calculation results of sound pressure at the 1st focus when absorption is considered, using lens type and liquid type as a parameter. As shown in Figure 9-1, ultrasonic frequencies at which sound pressure at focus become maximum increase in the order of Lens No.1 to No.4, or in other words, as the designed burst frequency $f_d$ becomes higher. Also, the maximum value of sound pressure itself becomes higher. In addition, as shown in Figure 9-2, frequencies at which sound pressure at focus become maximum increase in order of IPA, ethanol and water, or in other words, as absorption coefficient becomes smaller. Also the maximum value of sound pressure also becomes higher. Here, in Figure 4, while absorption coefficients of IPA, ethanol, and water are different at almost consistent intervals, the maximum values shown in Figure 9-2 are widely different between IPA and ethanol, and slightly different between ethanol and water. This is thought to be because the focal distance depends only on sound velocity, or in other words, wavelengths. Therefore, IPA and ethanol, whose sound velocities are slightly different, have almost the same focal distance and are affected only by the absorption coefficient. On the other hand, water, which has a different sound velocity, has a different focal distance. But largely affected by absorption due to higher frequency of maximum, it is thought that the difference from ethanol was reduced.

Taking the above into account, it is expected from the calculation with absorption being considered that the maximum value of sound pressure at focus, or in other words, the frequency at which ejection efficiency is maximized, is obtained at a lower point than the designed burst frequency and varies depending on the designed burst frequency of lens, the liquid absorption coefficient and liquid sound velocity.

In the experiment, the amplitude of RF burst waveform was fixed to 68Vpp, and the threshold of burst length at which drop starts to be ejected was measured at a deep portion of the focal depth to the cycle of approximately 7.7MHz described in section 5.2, or in other words, where transmissivity of the substrate is good. As shown in Figure 10-1, the
threshold of burst length shows a minimum value against the burst frequency. The frequency at which the threshold becomes a minimum becomes higher and the minimum value becomes lower in order of Lens No.1 to No.4. As shown in Figure 10-2, the frequency at which the threshold becomes a minimum becomes higher, and the minimum value becomes lower in order of IPA, ethanol, and water.

Here, we compare the calculated sound pressure shown in Figure 9-1 and 9-2 and the experimental energy threshold shown in Figure 10-1 and 10-2.

In Figure 11, the frequencies of the calculated values and experimental values that show their extreme values are compared. They showed basically the same tendencies, and especially when lenses whose designed burst frequency $f_d$ is 133MHz or higher (Lens No.3 No.4) were used in the experiment, they showed a good match.

Figure 12 shows a correspondence between the calculated maximum value of sound pressure at focus and the experimental minimum energy threshold. When lens and liquid are used as a parameter, the experimental energy threshold is lower when the calculated sound pressure at focus is higher, which coincides with the expectation except for results of the 2nd focus.

In Figure 13, all of the measurement points of the 1st focus in the calculation values in Figure 9-1 and 9-2 and the experimental values in Figure 10-1 and 10-2 are corresponded and compared. From an overall perspective, the experimental energy threshold is lower when the calculated sound pressure at focus is higher. However, some values significantly
deviate from our expectations. These are Lens No.1 and No.2, ethanol, and IPA that has a common characteristic where their frequency range in which drop can be ejected is narrow, as shown in Figure 10-1 and 10-2. For its cause, it is thought that the range where focusing efficiency increases exists on the low frequency side for Lens No.1 and No.2, and drop size is bigger. Therefore, these are more influenced by the kinetic energy of drop. For ethanol and IPA, it is difficult to form a drop due to small surface tension.

5.4 Drop Volume and Drop Velocity

As a characteristic of inkjet printing, it is essential to understand the drop volume that determines the dot size on paper and drop velocity that determines the location on paper where drop may hit. Therefore, we measured drop volume and drop velocity of ejected drop. The measurement was performed for each of the 1st and 2nd foci with fixed applied energy, using burst frequency as a parameter. For drop volume, the diameter of drop was measured and the volume of drop was calculated assuming that drop is sphere. For drop velocity, the average speed was measured in the area 300µm above the liquid surface where drop moves almost in a constant speed.

Measurement results of drop volume at RF burst length of 3µsec and 10µsec is shown in Figure 14. Drop volume becomes smaller as burst frequency becomes higher and its burst length becomes shorter. Drop volume by the 2nd focus exists on the extension of the curve by the 1st focus, which indicates that they show the same dependency on frequency.

Measurement results of drop velocity are shown in Figure 15. Drop velocity has a maximum value at a certain burst frequency. It is speculated that this is because it is affected by the dependency of the burst frequency of energy threshold shown in Figure 10-1, due to fixed applied energy, and the difference between the applied energy and energy threshold is maximized in the vicinity of the minimum value of the energy threshold, and sufficient energy is supplied.
5.5 Drop Modulation

Next, drop modulation in this method is described. As shown in Figure 14, because drop volume depends on burst frequency, it is possible to apply this characteristic to drop modulation. However, as shown in Figure 7, since the focal distance also depends on burst frequency, the liquid level also needs to be changed accordingly if the burst frequency is changed for drop modulation. However, on the actual inkjet print head, drop modulation needs to be performed with a fixed liquid surface level because of head structure. Therefore, we studied the utilization of the 1st and 2nd foci.

As shown in Figure 7-2, with Lens No.3, drop can be ejected at the 1st and 2nd foci, and each focus has a different dependency of focal distance on frequency. Therefore, if a liquid surface level at which drop ejection is possible is selected for both of the 1st and 2nd foci, it is possible to change drop volume by setting different burst frequencies for each focus while keeping the liquid surface level fixed. The result is shown in Figure 16. Here, in combination of Lens No.3 and water, the liquid surface level was fixed at 989µm and ultrasonic frequency was set to 92MHz (Figure 16(a)) and 177MHz (Figure 16(b)). Moreover, at the same time, applied energy was adjusted for each case to change drop size. As a result, drop volumes of 4.8pl and 1.2pl were obtained.

As described above, it was verified that drop modulation is possible with the use of an acoustic inkjet with fresnel lens by using focuses by the fundamental wave and second harmonic wave while adjusting applied energy.

5.6 Downward Ejection with Array Lens Head

This section describes the array lens head. To improve print speed, actual printers use array lens heads on which multiple lenses are arranged. In addition, it is preferable to eject drops in a downward because of the printer structure, and the liquid surface height is required to be fixed according to focal distance. Therefore, a plate with apertures is required to be installed on the liquid surface to maintain the liquid surface level.

Fresnel lens on the fabricated array lens head is shown in Figure 17. The lens pitch is 336µm. A cross section of the aperture plate is shown in Figure 18. To maintain the
surface liquid level precisely, the portion to retain the liquid surface of the aperture is made thin. Figure 19 shows downward drop ejection by the array lens head with aperture plate observed from the oblique direction. The aperture pitch is 336µm, which is the same as lens.

Next, the change of drop volume against the repetition frequency of drop ejection is shown in Figure 20. As a result of installing an aperture plate, surface wave caused by drop ejection reflects off the edge of the aperture, which causes the meniscus to oscillate. It is thought that if the next drop is ejected before this oscillation is fully attenuated, the ejection becomes unstable because the liquid surface level varies and reduces drop volume. In this case, the upper limit of repetition frequency for stable ejection is around 18 kHz.

6. Conclusion

Based on the experiments using a real device and the sound field calculations by Rayleigh's Equation, the following conclusions were obtained on acoustic inkjets with ultrasonic wave focused by fresnel lens.

[1] The results of the experiments and calculations showed a good match and we were able to understand the relations between ejection characteristics, and each parameter of lens, liquid, and drive condition. This makes it possible to design acoustic fresnel lens that realizes ejection characteristics that satisfies the desired image quality as inkjet printer.

[2] It was predicted by calculation and verified by experiment that drop modulation is possible by using focuses by the fundamental wave and second harmonic waves. This enables simultaneous achievement of both high image quality and high print speed for inkjet printers of this method.
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