 

# Printing with Ink Mist Ejected by Ultrasonic Waves

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## Abstract

A novel ink jet printing technology using ink mist jet has been developed. It enables multilevel printing within a single dot because a density controllable cluster of fine ink droplets is formed by focused ultrasonic waves.

The ultrasonic wave radiated into an ink chamber is reflected by the parabolic chamber wall and focused on a nozzle hole. Under the suitable driving condition of the ultrasonic transducer, a traveling surface wave is generated at the ink meniscus and it separates many fine ink droplets at the peak point of the wave. The density of the cluster can be controlled by changing the number of ultrasonic waves within the interval to achieve one dot printing.

We have obtained a print sample with reduced graininess using a prototype print head employing a 10 MHz transducer, which produces ink droplets with an average diameter of 2.5 µm. We also confirmed a basic performance having a maximum optical density of 2.3, 32 controllable gray levels and a resolution of 300 dpi using glossy paper with a dot frequency of 2 kHz.

## Introduction

The ink jet printer has in recent years made great progress in print quality, now conferring photo-like image quality. This is a tribute to the reduction in graininess, which was made possible by reducing the size of the ink jet droplets and the adoption of light-colored ink.

Another method of reducing graininess, called the ink mist printing system, has been proposed for a long time. [1, 2] It features multilevel printing for individual dots by forming them using a density controllable cluster (ink mist) of fine ink droplets. After the initial proposals, however, no papers or presentations have been made available which seriously addressed this system. This is because the proposed structure makes it difficult to improve the printing speed and resolution and difficult to ensure the reproducibility of color shades.

In this paper we propose a new mist jet print head structure using focused ultrasonic waves to solve these problems. The following sections present an overview of the new print head, the theory of and the experiments with its ink mist ejection characteristics, and the print quality provided by a prototype print head.

## Overview of the Print Head

### Basic Structure

Figure 1 shows a schematic sectional view of the basic structure of the mist jet print head. The piezoelectric transducer, which generates ultrasonic waves, is joined to the parabolic reflector via an insulating polymer film. The nozzle plate is located at the focal point of the parabolic reflector. Ink is supplied to the space surrounded by the reflector and film. A high-frequency voltage is applied to the drive electrode of the transducer, radiating an ultrasonic wave into the ink. The ultrasonic energy is reflected from the parabolic surface and concentrated on the focal point. The high-density ultrasonic energy atomizes the ink, ejecting it from the nozzle. The paper is maintained at a constant distance from the nozzle. The opposing electrode behind the paper applies a DC voltage between itself and the nozzle plate to electrostatically attract the fine ink droplets to the paper.

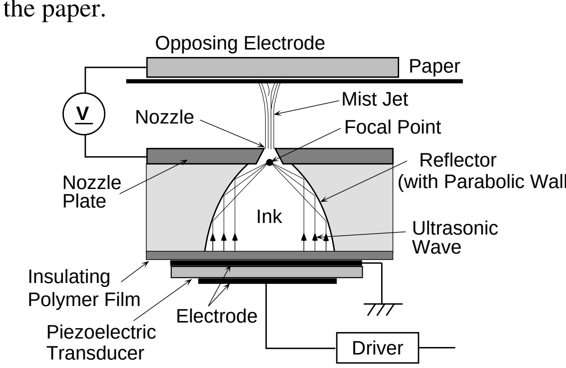



*Figure 1. Cross-sectional structure of the mist jet print head*

### Head Driving and Level Control

Figure 2 shows the head driving signals. A burst signal (b) is applied to the piezoelectric transducer to generate intermittently ultrasonic waves. This signal is generated by periodically turning on the basic signal (a) for a time length corresponding to the number of waves $n$. To increase the efficiency of ultrasonic wave generation, the basic signal frequency $f_o$ (=1/$T_o$) is set at the same level as the resonant frequency of the piezoelectric transducer. The burst frequency $f_b$ (=1/$T_b$) is matched with the eigen value of the meniscus oscillation to suppress any irregular meniscus oscillation.

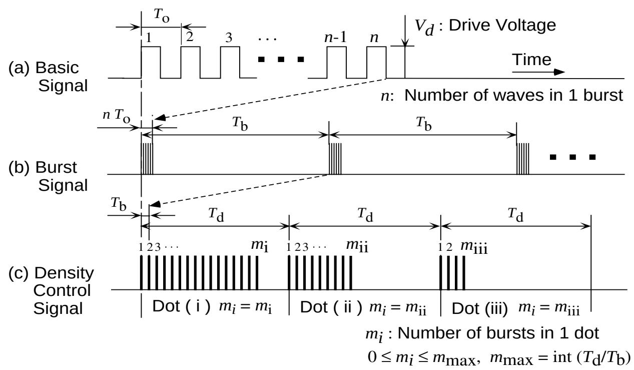



*Figure 2. Driving signals of the mist jet print head*

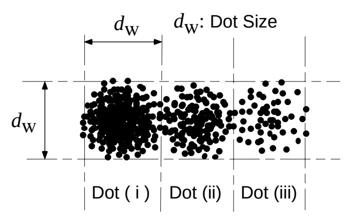



*Figure 3. Illustration of density controlled dots*

The amount of ink ejected during a burst is not enough to provide the required level for the maximum optical density for a dot. A dot is therefore formed by plural bursts. Thus the dot frequency $f_d$ (=1/$T_d$) is lower than that required to carry out a sufficient number of bursts for the maximum optical density. The dot density control signal (c) specifies one of three different numbers of bursts and hence different optical densities for individual dots.

In Figure 3, the dots thus printed are called dots (i)-(iii). The density control signal regulates the number of fine droplets which form each dot and hence its optical density.

## Ink Mist Ejection Characteristics

### Model for Fine Droplet Separation

It is thought that fine ink droplets separate from the peak points of the surface wave on the meniscus in the nozzle opening. First, let us consider how an ultrasonic wave incident perpendicularly to the surface (longitudinal wave) produces a surface wave (transverse wave). Figure 4 shows an excited surface wave on the meniscus and fine droplets separating from its peak points. Because the nozzle diameter is smaller than the wavelength, the ultrasonic wave oscillates the whole meniscus with its particle velocity $u$ being almost in phase. At this time the ends of the meniscus are securely held by the nozzle edge. It is therefore assumed that the ultrasonic wave excites a surface wave that travels from the nozzle edge to the center at velocity $v_c$. Generally, the velocity $v_c$ of a surface wave is given by equation (1), from the surface tension $\sigma$ and density $\rho$ of the liquid (ink) and the wavelength $\lambda_c$: [3]

$$v_c = \sqrt{2\pi\sigma/(\rho\lambda_c)} \quad (1)$$

The wavelength $\lambda_c$ is expressed by equation (2) as a function of the excitation frequency $f_o$:

$$\lambda_c = \sqrt[3]{2\pi\sigma/(\rho f_o^2)} \quad (2)$$

The displacement amplitude $d_c$ of the surface wave can be obtained by multiplying the displacement amplitude of the piezoelectric transducer by the focusing magnitude and the transmission efficiency of the ultrasonic wave. Therefore the amplitude $d_c$ is almost proportional to the drive voltage. Assuming that droplet separation begins when $d_c$ surpasses the wavelength $\lambda_c$, [4] the condition for ink mist ejection is given by equation (3):

$$d_c = \alpha V_d > \lambda_c \quad (3)$$

where $\alpha$ is a coefficient concerning the focusing magnitude and the transmission efficiency of the ultrasonic wave.

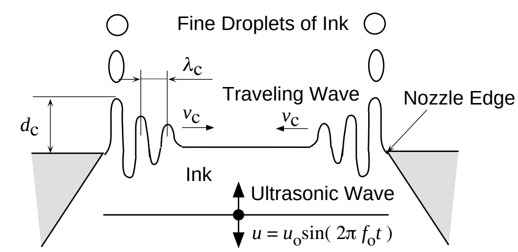



*Figure 4. Illustration of traveling wave on the surface of ink meniscus*

## Experiment

### (i) Prototype Head

The prototype multi-head has a staggered arrangement of two rows of eight head elements. Figure 5 shows a cross section and the major dimensions of the multi-head. The reflector has 16 parabolic holes, and the nozzle plate has 16 tapered holes. All these holes were machined. The reflector and nozzle plate are made of a metallic material to achieve a high reflectance of the ultrasonic wave on the reflector and to prevent erosion by the ultrasonic wave on the nozzle plate. The piezoelectric transducer has a common electrode on one side and separate drive electrodes on the other. The basic frequency $f_o$ of the head is 10 MHz.

### (ii) Experimental Results

Figure 6 shows photos of the ink mist ejection when the number of waves $n$ was set at 6, and were obtained using a laser stroboscope (Laser Strobe System: Control Vision Inc). The ultrasonic wave, radiated from the transducer, propagates in the ink and reaches the nozzle in approximately 1.4 µs. The values of $T_s$ shown below the photos are the elapsed time after the arrival of the ultrasonic wave ($T_s$ = 0). The photos were taken as a moving image by synchronizing the burst signal and the strobe signal with the CCD imaging rate (1/30 s). The ink mist ejection is considered highly reproducible because the image could be observed almost still when the strobe signal was fully synchronized with the burst signal. Also, the photos show that the ink mist is ejected chiefly from the ends of the meniscus (nozzle edges). From the fact that when $T_s$ =1.0 µs the front end of the mist is 30 µm away from the meniscus, the ink mist ejection velocity is estimated to be approximately 30 m/s.

Figure 7 shows the relationship between the ejection flow rate of the mist and the drive voltage. Using the number of waves $n$ as a parameter, the measurements were conducted by applying a continuous burst signal with a frequency $f_b$ of 64 kHz. The ejection flow rate was calculated from the reduction in head weight after 300 seconds of driving. With a higher number of waves $n$, ink mist ejection starts at a lower voltage, and the flow rate increases more sharply with an increase in the drive voltage. According to equation (3), however, the ink mist ejection ought to start at a constant voltage regardless of the number of waves. This may be explained as follows: in the range of the numbers of waves used here, the transducer is in a transient state that precedes the stationary resonant state. Thus, the actual amplitude is smaller for a lower number of waves. For each number of waves, the flow rate declines as the drive voltage exceeds a certain level. This is probably because when the radiation pressure of the ultrasonic wave surpasses a certain value, the nozzle edges can no longer hold the end of the meniscus, reducing the efficiency of surface wave generation. Under the test conditions, six waves ($n$ = 6) maximized the ejection flow rate of the mist.

Figure 8 shows the distributions of ink droplet diameters directly measured using a particle size distribution measuring device based on laser scattering (LDSA-2400A: TCA). When the drive voltage $V_d$ is 45 V (a), a uniform ink mist is produced in which around 80% of the droplets have diameters between1.5 and 3.5 µm. From equation (2), the surface wave excited on the meniscus has a wavelength $\lambda_c$ of approximately 1.5 µm. It is therefore confirmed that the diameter is in the same order as the wavelength. When $V_d$ = 53 V (b), the distribution has two peaks, one around 3 µm and the other around 12µm.

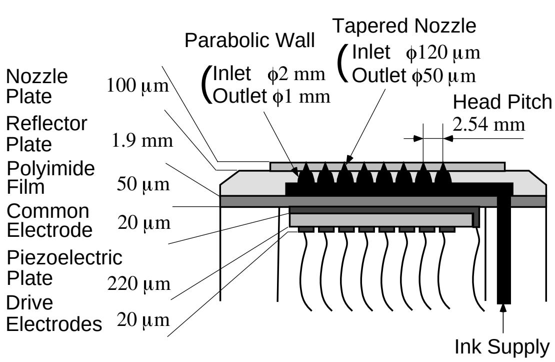



*Figure 5. Cross-sectional structure of prototype mist jet print head with 16 elements*

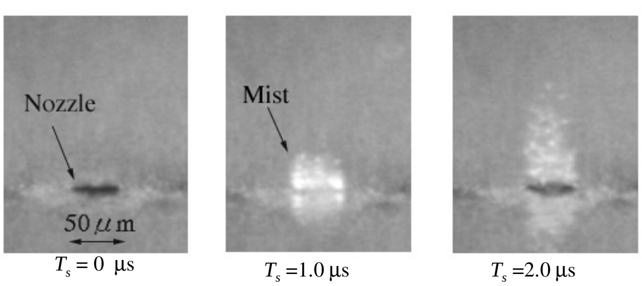



*Figure 6. Photos of ink mist ejection at $f_o$ = 10 MHz, n = 6*

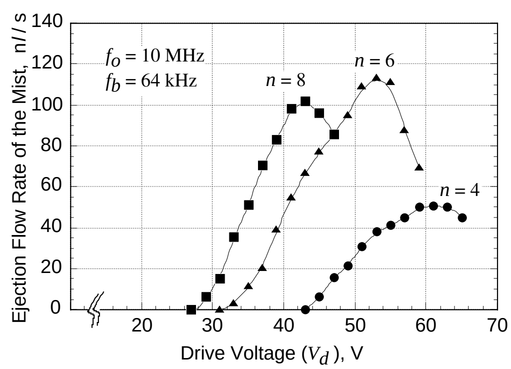
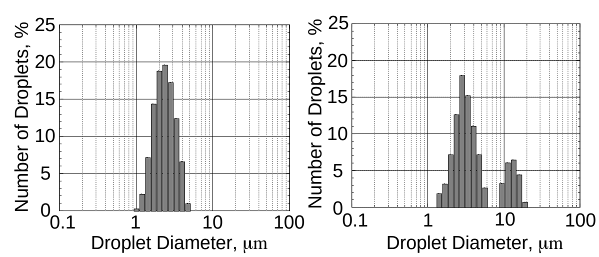



*Figure 7. Relationship between ejection flow rate of the mist and drive voltage*




(a) $V_d$ = 45 V, $n$ (b) $V_d$ = 53 V, $n$

*Figure 8. Distributions of droplet diameter in the mist jet*

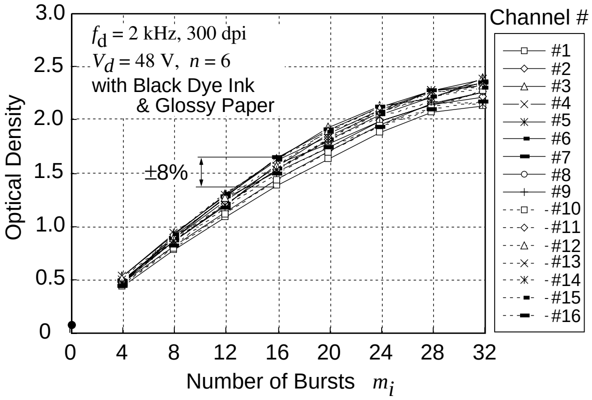



*Figure 9. Relationship between optical density and number of bursts in each of 16 head channels*

## Printing Test

**Printing Conditions**

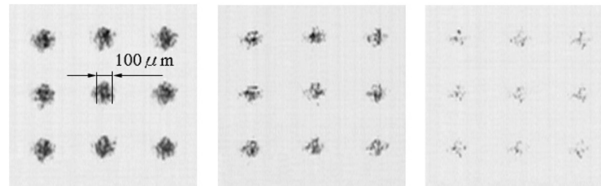
The prototype printer fabricated to test the printing characteristics employs the same scanning system as existing printers. The main and secondary scanning operations are done by the head motion and paper feed, respectively. We used a dye-based prototype ink and commercially available glossy paper (HG-201: Canon). A preliminary test showed that at a print resolution of 300 dpi, the printer needs approximately 45 p*l* for each dot to obtain an optical density of 2.3. To achieve this level of optical density with a dot frequency $f_d$ of 2 kHz, a set of conditions was identified in which an ejection flow rate of 90 n*l*/s could be obtained: number of waves $n$ = 6, drive voltage $V_d$ = 48 V and burst frequency $f_b$ = 64 kHz from the data shown in Fig. 7. Under this set of conditions, the print head carries out up to 32 bursts ($m_{max}$ in Fig. 2) during the printing of one dot. The gap between the nozzle and paper was approximately 0.5 mm. A DC voltage of 200 V was applied between the opposing electrode and the nozzle plate.

**Printing Characteristics**

Figure 9 shows the relationship between the optical density and the number of bursts $m_i$. A gradation pattern was printed using each of the 16 head channels, and the optical density was measured at every fourth burst increment. The results show that the maximum difference in the optical density is around ±8% between the channels. Also, all channels exhibit density saturation characteristics.

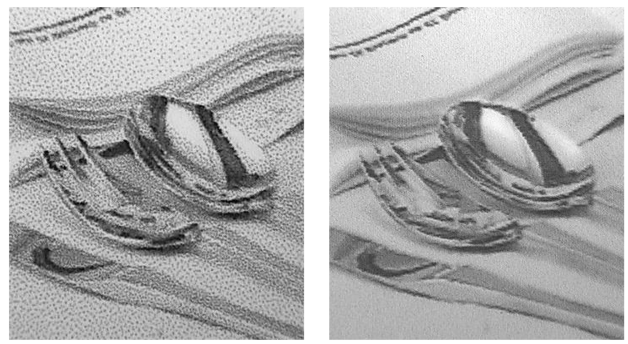
Figure 10 shows photos of density controlled dots for different numbers of bursts. As we saw in Fig. 3, each dot consists of small ink spots. The density of these spots varies with the number of bursts. The dot has a size of approximately 100 µm, which is appropriate for printing at a resolution of 300 dpi.

Figure 11 shows enlarged views of a color image printed using a conventional printer with light-colored ink (a) and the prototype printer (b). In the prototype print head, one channel was used for each of the four colors (Y, M, C and Bk). The comparison reveals that the prototype head remarkably reduces the graininess of the highlight areas.




(a) $m_i = 32$ (b) $m_i = 12$ (c) $m_i = 4$

*Figure 10. Photos of the density controlled dots*



(a) Conventional Ink (b) Prototype Mist

*Figure 11. Photos of enlarged images printed by prototype mist jet and existing ink jet ( Part of a SCID image x4 )*

## Conclusion

The authors have developed a new system for mist jet print heads using focused ultrasonic waves, and conducted theoretical and experimental investigations of the ink mist ejection characteristics. It has been established that when driven by a 10 MHz burst signal, the head ejects an ink mist, which is composed of fine droplets with an average diameter of 2.5 µm with good reproducibility.

A printing test revealed that the new system provides a maximum optical density of 2.3, 32 controllable gray levels in one dot and a resolution of 300 dpi using glossy paper with a dot frequency of 2 kHz, remarkably reducing the graininess of the printed image.

To put the new head into practical use, it is necessary to develop the system to achieve long-term reproducibility and reliability, and to reduce costs. When solutions to these problems are available, the new system will be promising.

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## Biography

Hiroshi Fukumoto received his B.E. and M.E. degrees in Mechanical Engineering from the Tokyo Institute of Technology in 1983 and 1985, respectively. He joined Mitsubishi Electric Corporation in 1985. Since then, he has been working on the research and development of sheet handling mechanisms for printers and facsimiles. His current research interest is advanced printing technology. He is a member of the Japan Society of Mechanical Engineers.