Ink Jet Printing with Focused Ultrasonic Beams

Isao Amemiya, Hitoshi Yagi, Kenichi Mori, Noriko Yamamoto, Shiro Saitoh, Chiaki Tanuma and Shuzo Hirahara
Research and Development Center, Toshiba Corporation, Kawasaki, Japan

Abstract

Novel ultrasonic ink jet printing technologies promising high resolution, high quality and high speed printing have been proposed and investigated. The printing head is capable of ejecting small droplets from free liquid surface without nozzles, and therefore, is favorable for the fabrication of a line head covering a full-width of the paper.

Notable beam focusing and scanning technologies have been presented. Ultrasonic beams generating droplets have been formed by electronically focusing with rectangular transducer arrays and a one-dimensional Fresnel lens. Further, the beam positions can be scanned electrically at a fine pitch corresponding to that of transducer arrays. Only one line head could achieve a high resolution printing in line, which was not possible using the conventional heads with arrayed pairs of a transducer and a lens. The heads' planar multilayer structure makes possible production of practical line head for very high resolution using microfabrication technologies such as photolithography.

We report results obtained experimentally for droplet ejection and scanning based on our concepts, using printing heads composed of 50 MHz transducer arrays at the pitch of 85 µm.

Introduction

Ink jet printing technologies have recently been greatly improved, especially in regard to the quality of photographic images and the print reliability of waterfastness, lightfastness and bleeding. However, the printing speed of color images remains a serious problem.

A log size head covering a full-width of the paper would make it possible to speed up printing remarkable, and therefore, many researchers have investigated this approach using various technologies. Because widely used technologies, such as thermal ink jet (bubble jet) and piezo impulse ink jet, require nozzles, line head is subject to the grave problems of low reliability due to clogging and high manufacturing costs; problems which worsen in the case of high resolution printing.

The basic technology for ink jet printing using ultrasonic beams was proposed in the early 1970s.[1] The notable characteristic of this technology is its capability of ejecting small droplets from free ink surface without nozzles and orifices, so the clogging does not become a grave problem and, if it does occur, is easily solved. Therefore, this ink jet printing technology is suitable for the line head fabrication with thousands of ejectors. Additionally, size of a generated droplet can be smaller in proportion to the frequency of ultrasonic waves, and so high resolution printing can be achieved.

Elrod *et al.*[2-4] reported an experimental and theoretical investigation of droplet ejection using focused ultrasonic beams and examined the application to line head printing. Their printing head structure had arrayed pairs of a traducer and a lens, and so ejecting at a fine pitch with one head was difficult, because lenses with much larger diameter than a droplet size were required to focus ultrasonic waves. Thus, several line heads were deployed for the high resolution printing.

We have proposed and investigated novel beam focusing and scanning technologies for ultrasonic ink jet printing, that are capable of achieving high resolution, high quality and high speed printing with a line head. The head has a planar multilayer structure suitable for mass production, making it possible to manufacture practical line head for very high resolution using microfabrication technologies such as photolithography. We report results obtained experimentally for droplet ejection and scanning based on our concepts, using printing heads composed of 50 MHz transducer arrays at the pitch of 85 µm.

Principle of Ultrasonic Line Heads

Electronic Focusing

The phased array technologies widely used in the radio field, for example, for radar, can be applied to focusing ultrasonic beams for ink droplet ejection. Figure 1 shows the schematic diagram of electronic focusing with transducer arrays. Rectangular transducers arrayed in line at even pitch are employed and placed in ink liquid. RF signals with time-delays, which are assigned to each transducer element so that ultrasonic waves radiated into ink liquid can be in phase at the focal point, have been applied.

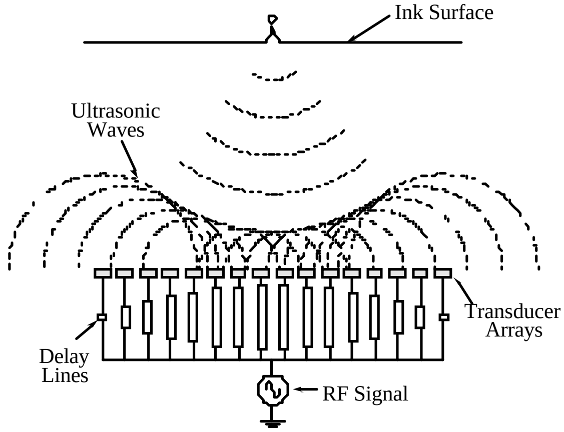

Figure 1. Schematic diagram of electronic focusing with transducer arrays.

The delay time τ_i of an i transducer element is given as

$$\tau_i = \frac{d}{2vF}\left\{\left(\frac{N-1}{2}\right)^2 - \left(i-\frac{N+1}{2}\right)^2\right\} \; (i=1,2,\text{---},N) \quad (1)$$

where d is the pitch of transducer elements, v is the sound velocity in ink liquid, F is the focal length and N is the number of transducer elements.

Delay times for each element can be controlled by focusing the ultrasonic beam at any point on ink surface. For ink jet printing head, however, symmetrical time-delay assignments in transducer arrays as shown in Figure 1 are desirable, because non-symmetrical time-delay assignments may make the droplet ejecting direction not perpendicular, which reduces the addressability of spots on a paper. The electronic focusing method makes possible adjustment of the focal point and beam conditions as occasion demands without device remodeling.

Electronic Scanning

The ultrasonic beam formed by electronic focusing using plural transducer arrays can be scanned electronically in a fine pitch along arrays.

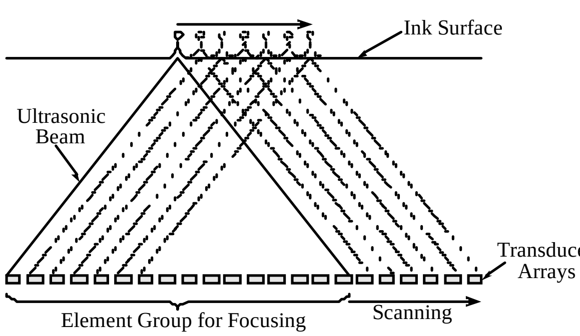

Figure 2. Schematic diagram of electronic scanning along transducer arrays.

Figure 2 shows the schematic diagram of a linear electronic scanning of ultrasonic beams. Scanning the group of transducer elements for focusing a ultrasonic beam in arrays have changed the position of droplet ejection on the ink surface. Using uniform ultrasonic beams, droplet position on ink surface can be moved at the same fine pitch as a transducer elements.

Design of Ultrasonic Line Heads

Simplification of Drive Circuits

The electronic focusing using a quadratic functional distribution of time-delays, as shown in Figure 1, requires complex drive circuits. In particular, at the high frequency and short focal length applied for ink jet printing heads, minute controls of delay times are required. Therefore, we propose a simpler focusing method based on the theory of Fresnel zone plate. Figure 2 shows the schematic diagram of electronic Fresnel focusing.

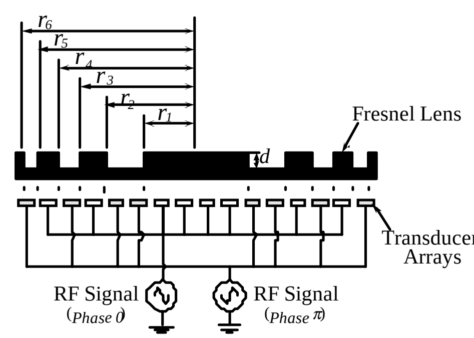

Figure 3. Schematic diagram of a cross-sectional Fresnel lens and assignment of RF signal phased arrays to transducer elements.

This focusing method imitates an electronic Fresnel lens, that is, only two kinds of signal phases (or delay times) have been used. The upper drawing in Figure 3 is the cross section of a planar Fresnel lens, having grooves on the radiation surface. The widths and positions of grooves have been designed according to the theory of Fresnel zone plate, waves radiated from grooved regions having an opposite phase to that from ungrooved regions.

The assignment of RF signals has been determined by the position of transducer elements for the Fresnel lens pattern; elements facing an ungrooved region are assigned the standard phase (called *phase 0*) and elements facing a grooved region are assigned opposite phase to the standard one (called *phase* π). It is of no consequence which signal phase is standard and that the difference of phases is given by time-delays.

At a focal length of 2.5 mm and a focusing group of 16 elements arrayed at the pitch of 85 μm with 25 μm gaps, the signal phase array assigned for electronic Fresnel focusing is shown in Table 1.

Table 1. Assignment example of signal phases at a focal length of 2.5 mm and a focusing group of 16 elements arrayed at the pitch of 85 μm with 25 μm gaps

No. of element	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Signal phase	π	*0*	π	*0*	π	π	*0*	*0*	*0*	*0*	π	π	*0*	π	*0*	π

Figure 5 shows simulated ultrasonic beam profiles in the azimuth plane at a focal length of 2.5 mm using the electronic Fresnel focusing with signal assignment as per Table 1, compared with the conventional electronic focusing. Both main center beams and grating side lobes at 0.9 mm distance from the center are similar to those of the conventional electronic focusing. The grating side lobes are generated inevitably when the element pitch is larger than wavelength of ultrasonic waves. The profile with the electronic Fresnel focusing has higher side lobes around the main beam, because denying mutuality of waves may be insufficiency as a result of using only two kinds of wave phases. Nevertheless, their levels are considerably lower than a main beam and grating side lobes.

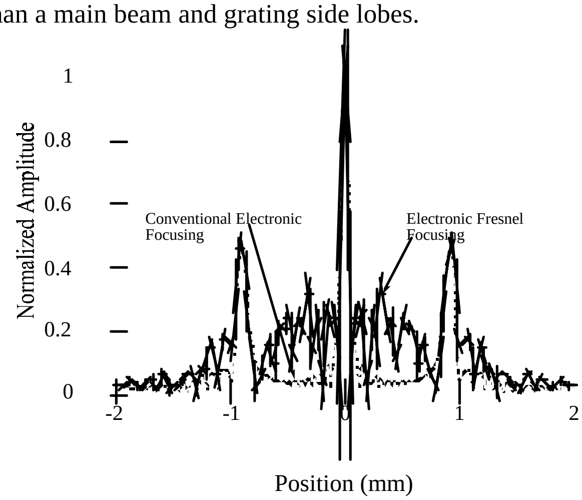

Figure 4. Simulated ultrasonic beam profiles in the azimuth plane at a focal length of 2.5 mm using electronic focusing with 16 elements.

The electronic Fresnel focusing with only two kinds of RF signals whose phases are opposite to each other has been found to form ultrasonic beams similar to those formed by conventional electronic focusing with quadratic functional time-delay distribution. The construction of drive circuits has been simplified exceedingly.

One-dimensional Fresnel Lens

An acoustic lens based on the theory of Fresnel zone plate has been used for focusing in a rectangular direction with transducer arrays. An conventional acoustic Fresnel lens is composed of a number of concentric annular grooves with designated depth.[5] For combination with electronic focusing by transducer arrays, we propose the one-dimensional Fresnel lens with a striped structure.

The cross section of an acoustic Fresnel lens is shown in Figure 3. The radius r_n of each zone has been determined so that waves radiated from the grooved and ungrooved regions interfere reciprocally at a focal point, which can be given by

$$r_n = \sqrt{\frac{2(n-1)\lambda_i}{2}\left(F + \frac{2(n-1)\lambda_i}{8}\right)} \quad (n=1,2,\text{---}) \qquad (2)$$

where n is the number of the edge, F is the focal length and λ_i is the acoustic wavelength in an ink liquid. The depth d of grooves has been determined so that waves radiated from the grooved regions have a phase opposite to that from the ungrooved regions, which can be given by

$$d = \frac{(2m-1)}{2\left(\frac{1}{\lambda_i} - \frac{1}{\lambda_l}\right)} \quad (n=1,2,\text{---}) \qquad (3)$$

where m is a natural number and λ_l is the acoustic wavelength in lens materials.

The one-dimensional Fresnel lens can be combined with the function of an acoustic matching layer, because of its planar structure. The acoustic matching layer is used for transmitting efficiently ultrasonic waves from transducers to ink liquid. It is desirable for the specific acoustic impedance Z_m of an acoustic matching layer to be close to the geometric mean between that of piezoelectric material and ink liquid as follows,

$$Z_m = \sqrt{Z_p \cdot Z_i} \qquad (4)$$

where Z_p is the acoustic impedance of a piezoelectric material and Z_i is the acoustic impedance of ink liquid. Further, it is desirable for the thickness t_m of an acoustic matching layer to be close to the values given by

$$t_m = \frac{2n-1}{4}\lambda_m \quad (n=1,2,\text{---}) \qquad (5)$$

where n is a natural number and λ_m is the acoustic wavelength in an acoustic matching layer. The ultrasonic waves are not reflected at interface of the layer having the thickness given by Equation (5).

In choosing the material for an acoustic lens, it is important to ensure that the specific acoustic impedance is close to the values given by Equation (4) and the thickness of each grooved regions and ungrooved regions satisfies Equation (5) as an acoustic matching layer.

Printing Head Structure

Figure 5 shows the geometric drawing of a prototype printing head structure designed on our line head principles, in which ink chamber is omitted.

The printing head has a multilayer structure on a substrate. Transducer arrays composed of piezoelectric materials sandwiched by electrodes have been attached to the substrate. The bottom electrodes are arrayed at a fine pitch. The one-dimensional Fresnel lens combined with the acoustic matching layer has been attached to the top of transducer arrays. The structure is simple and planar, and thus the printing head is highly suitable for mass production. The head for very high resolution printing can be product using microfabrication technologies such as photolithography.

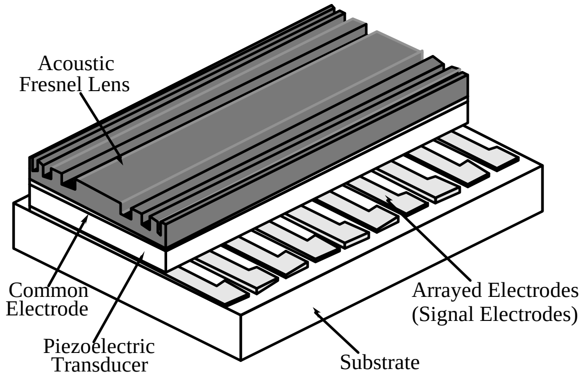

Figure 5. Structure of printing head with transducer arrays.

Experimental Procedure

A prototype printing head designed in accordance with the principles shown in Figure 5 has been fabricated. As the frequency of ultrasonic waves capable of ejecting droplets with diameter of approximately 30 μm, 50 MHz has been used according to preliminary experimental results for the single ejector with a concave transducer.

Lead titanate ceramics ($PbTiO_3$) have been used for piezoelectric transducer radiating ultrasonic waves. $PbTiO_3$ ceramics have anisotropic characteristics in oscillation modes and a high electromechanical coupling constant of over 50 %, which signifies a conversion efficiency between electrical and acoustic fields, and is suitable for usage of relative high frequency of over 10 MHz. $PbTiO_3$ ceramics were polished mechanically up to the thickness of 45 μm, a value determined by the required frequency of 50 MHz and the frequency constant particular to materials. On the bottom of piezoelectric transducers, gold electrodes with a titanium adhesion layers (Au/Ti) were deposited and etched into arrays. The electrodes were evaporated in high vacuum and patterned using photolithographic technologies. The thickness of Au and Ti layers is 300 nm and 30 nm, respectively. A pitch of the arrays is 85 μm and a width of the elements is 60 μm. A common Au/Ti electrode, whose thickness is the same as that of the arrayed electrodes, was deposited on the top of piezoelectric transducers. The width of common electrode is 1.4 mm, same as the aperture width of an acoustic Fresnel lens. Both electrodes were led on the glass substrate and connected to drive circuits.

Filled epoxy resin was used for the acoustic Fresnel lens material, whose sound velocity is approximately 3000 m/s. The groove depth of Fresnel lens was required to be 30 μm, according to Equation (4) at the ultrasonic frequency of 50 MHz and the sound velocity in ink liquid of 1500 m/s. The thickness of grooved and ungrooved regions is 15 μm and 45 μm respectively, which satisfy Equation (5). The lens layer was polished mechanically up to the thickness of 45 μm and the grooved regions were formed mechanically with blades at the positions according to Equation (2).

The glass substrate was mounted on a printed circuit board (PCB) connected with drive circuits. In the experiment of droplet ejection, the open pool of ink liquid was attached to lens. A water-based ink liquid and a silica-coated ink jet paper were used and the paper was positioned approximately 3 mm above the ink surface.

Experimental Results

Figure 6 shows a photograph of a droplet ejecting from free ink surface by an ultrasonic beam focused with 16 transducer elements.

A droplet size is approximately 30 μm as expected, which is equal to the acoustic wavelength in ink liquid. The droplet is a sphere without tails, which is characteristic of ink jet printing using focused ultrasonic waves. The results demonstrated that the ultrasonic beam formed complexly by electronic Fresnel focusing and the one-dimensional Fresnel lens can eject droplets similar to those ejected by a single lens.

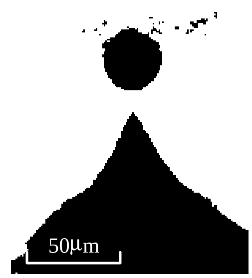

Figure 6. Photograph of droplet ejecting from free ink surface. The diameter of a droplet is approximately 30 μm.

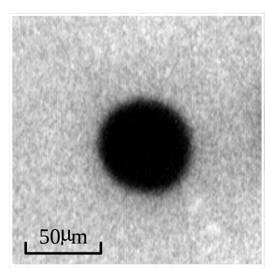

Figure 7. Photograph of a spot on silica-coated paper. The diameter of a spot is approximately 60 μm.

Figure 7 shows the photograph of a spot on a silica-coated ink jet paper. The diameter of a spot is approximately 60 μm and is applicable to high resolution printing of over 600 dots per inch (dpi). The droplet struck the paper and spread to fill an area with a diameter approximately twice that of the droplet diameter. The spot has a very round shape with no satellite and yields high quality printing.

Figure 8 shows the photograph of 32 spots on a silica-coated ink jet paper when ultrasonic beams were scanned electronically consecutively. The positions of spots were moved in the same pitch as that of transducer elements. The addressability of spots is within 0.8 times in the spot diameter. The position errors may have been caused by the turbulence of an atmosphere. It is thought that position errors would be reduced by putting the paper closer to the ink surface.

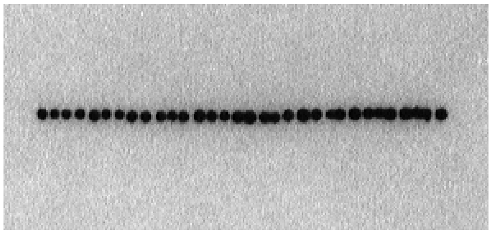

Figure 8. Spots on paper during electronic scanning of an ultrasonic beam consecutively.

Conclusion

Novel beam focusing and scanning technologies for ultrasonic ink jet printing have been proposed, which can achieved high resolution, high quality and high speed printing with a line head. Droplet ejection from a free ink surface without nozzles and scanning at a fine pitch, using printing heads composed of 50 MHz transducer arrays, have demonstrated experimentally the validity of our concepts. The heads have a planar multilayer structure suitable for mass production and microfabrication, and very simple drive circuits have been designed. The results show the possibility of producing practical line heads covering a full-width of the paper for high resolution printing.

References

1. K. A. Krause, *IBM Technical Disclosure Bulletin*, Vol. 16, No. 4, pp. 1168, September 1973.
2. S. A. Elrod, B. Hadimioglu, B. T. Khuri-Yakub, E. G. Rawson, E. Richley, C. F. Quate, N. N. Mansour, and T. S. Lundgren, J. Appl. Phys., Vol. 65, No. 9, pp. 3441-3447, May 1989.
3. B. Hadimioglu, S. A. Elrod, M. Lim, D. L. Steinmetz, J. C. Zesch, B. T. Khuri-Yakub, E. G. Rawson, and C. F. Quate, *Proceeding of IS&T International Congress on Advanced in Non-Impact Printing Technologies*, pp. 411-415, 1992.
4. B. Hadimioglu, S. A. Elrod, D. L. Steinmetz, M. Lim, J. C. Zesch, B. T. Khuri-Yakub, E. G. Rawson, and C. F. Quate, *Proceeding of 1992 IEEE Ultrasonics Symposium*, pp. 929-935, 1992.
5. K. Yamada and H. Shimizu, *Proceeding of 1985 IEEE Ultrasonics Symposium*, pp. 755-758, 1985.