Development of Drop-on-Demand Piezoelectric Line Inkjet Printhead

Atsushi Hirota, Brother Industries, Ltd., Nagoya, Aichi, Japan; Shin Ishikura, Kyocera Corporation, Kokubu, Kagoshima, Japan

Abstract

The authors developed a drop on demand piezoelectric line inkjet printhead composed of a monolithic structure having resolution of a 600dpi in 4.25 inch print width. The printhead is provided with plural trapezoidal regions of 1-inch width approximately, in which parallel array of rhombic pressure chambers are arranged in matrix form. The trapezoidal regions are aligned in print width direction, with their oblique side facing each other, in order to set 2,656 nozzles communication with corresponding chambers, in an area of 4.25 × 0.66 inches. This monolithic structure allows easy elongation in print width just by increasing the number of trapezoidal regions. Power consumption was reduced to less than 1/10 of that of the former models per nozzle by modifications in configuration of a piezoelectric actuator and pressure chamber. Materials of the printhead were chosen to accept various fluid chemicals. The printhead showed the reliability of over 10 billion dots per nozzle at the endurance test. Full color images were obtained with a resolution of 600 × 600 dpi and 4 grade grayscale at a paper-feeding rate of 847 mm/sec by six printheads arranged in parallel, which corresponded with aqueous inks of different colors respectively.

Introduction

Inkjet technology is one of the printing technologies, which enables non-impact printing with a relatively simple device structure. This technology has been widespread use in consumer-oriented printers as inkjet printer, due to the penetration of PCs, digital cameras, and the Internet. Of these printers, so-called multifunction printers, which combine printing by inkjet technology with other functions such as scanning, copying and faxing, were originally developed for SOHO. However, the multifunction printers are rapidly expanding their market over the fence between SOHO and personal use because of their lower price and convenience. An attempt to bring the inkjet technology into corporate-office market has been also made, for example, by specialized inkjet printers.[1] Improvements in inks and printheads have realized inkjet printers capable of printing on plain papers with high printing speed. In addition, potential demands on inkjet technologies are high for their non-impact capability. Thus, it is expected that the needs would rapidly grow with the advantage of the inkjet technologies.[2]

However, in spite of their expansions in applications, there have been negative stereotypes with inkjet in their printing speed, namely, excellent in quality, but poor in productivity. Therefore, the authors started development of a new printhead based on targets represented by such keywords as “fastness” and “applicability”. Firstly, the authors aimed to break incompatibility of conventional inkjet technology in printing speed with quality. Secondary, they took applicability to both printing sizes and ink types into account for the concept. Their objectives for the development fixed at the beginning are summarized as follows:

1. Superiority in printing speed for dramatic progress in printing productivity by inkjet technology
2. Structure that is simple, compact and extendable along a printing width
3. The possible lowest driving voltage for the effectiveness in cost and power consumption that distinguishes inkjet technology from electrophotography technology
4. Applicability to various types of ink

The authors have concluded that a line inkjet printhead in a monolithic structure with unimorph piezoelectric actuators could be an appropriate solution for the objectives. Representative specifications of the developed printhead are shown in Table 1. These results were obtained by discharging inks used for inkjet Multi-Function Centers® of Brother Industries, LTD.

Table 1: Specifications of Printhead

1. Size (width x depth x height)	152 x 22 x 1 mm
2. Number of nozzles	2,656 nozzles per head
3. Print width	108 mm (4.25 inches)
4. Resolution	600dpi (in print width direction)
5. Drive frequency	Up to 20 kHz
6. Number of droplet sizes	4 (3, 7, 14, 21 pL)
7. Driving voltage	Standard 17 V (maximum: 24V)
8. Required power	2.5 mW / nozzle Approx. (During continuous use at standard voltage and maximum drive freq.)
9. Print speed	847mm / sec. (at 600 dpi resolution in paper feeding direction)
10. Reliability	10 billion or more dots / nozzle (under investigations)

This paper covers studies on printhead design, especially on forms of cavities and layered structures of piezoelectric actuators and it also covers summaries on printing capabilities.

Features of Line Inkjet Printhead

Figure 1 shows an appearance of a primary part of the developed line inkjet printhead.

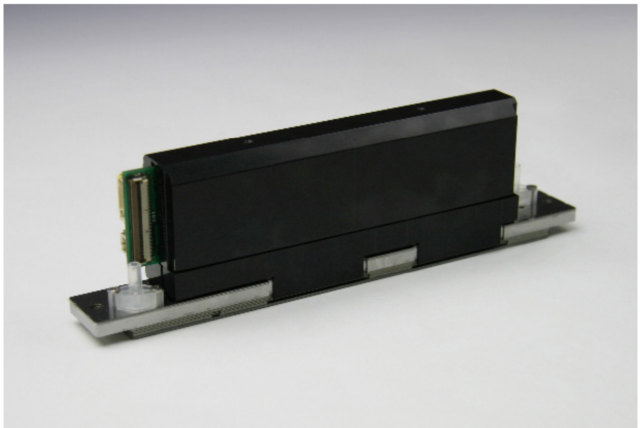


Figure 1. Appearance of line Inkjet Printhead.

Structure of Printhead

A printhead includes two mechanical units and electrical components such as COFs, i.e. chip on flexible circuits. Of these mechanical units, the first unit includes pressure chambers, manifolds, nozzles and piezoelectric actuators. The second unit basically functions as an ink reservoir for supplying ink to the first unit and holds a circuit board thereon. The first and second units are called front end unit and back end unit, respectively.

Figure 2 is a plain view of the front end unit on which piezoelectric actuator units are mounted. The front end unit is formed of flat components, such as filters, actuator units and several thin plates, in which nozzles and channels are opened, by bonding to each other with epoxy adhesive. The thin plates are made of SUS430 for anticorrosion. Four trapezoidal actuator units with a width of a little over 1 inch are arranged on the top thin plate, which is called a cavity plate, with a slight gap between each of them.

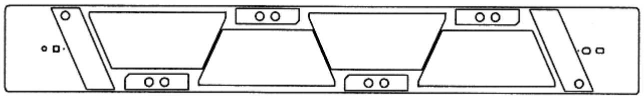


Figure 2. Front end unit.

Figure 3 shows an arrangement of cavities or pressure chambers in a cavity plate. There are 2,656 cavities formed in the plate by chemical etching. There are 664 cavities are arranged under each of the actuator units. In the cavity unit, sixteen rows of cavities are arranged in its direction. Each of rows includes 166 cavities, which are aligned in a print width direction at a density corresponding to 37.5 dpi.

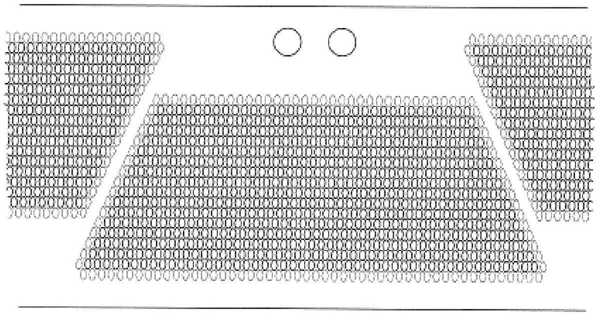


Figure 3. Arrangement of cavities in cavity plate.

One of the thin plates called a nozzle plate has 2,656 nozzles communicating with the corresponding cavities. The nozzles are aligned in the same pitch as the cavities. There are sixteen rows of nozzles in the nozzle plate with an offset of 1/600 inch in the print width direction therebetween, and this arrangement achieves a resolution of 600 dpi.

The ink reservoir in the back end unit supplies ink for manifolds in the front end unit through filters. Hence, the channels from the manifolds to the nozzles are filled with the ink. Figure 4 is a cross-sectional view of an individual channel from a manifold to a nozzle.

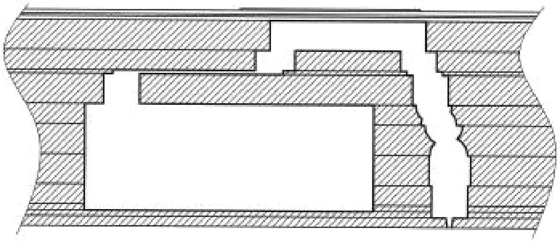


Figure 4. Cross sectional view of individual channel.

Figure 5 shows an arrangement of the manifolds in the front end unit. As shown in Figure 5, there are four linear manifolds, each of which serves ink for cavities in four rows. In the four manifolds, the upper two manifolds are paired, the lower two manifolds are paired, and the upper pair and the lower pair of manifolds are independent of each other. Five each of the inlets are arranged corresponding to the each pair of manifolds in order to supply ink to each pair of manifolds. With this structure, printing can be performed by using two different colors of ink filled in the upper and lower pairs of manifolds in one front end unit respectively. In this case, the resolution of printed image is 300 dpi.

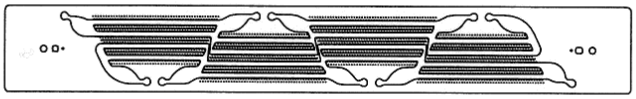


Figure 5. Arrangement of manifolds

Compactness and Applicability to Various Printing Widths

Configurations of the actuator units as well as channel structures were examined for a compact design. Firstly, it was assumed that a depth of the printhead or a dimension in paper feeding direction was determined by boundary configurations between the plural actuator units in addition to the depth of actuator units. As shown in Figures 2 and 3 above, the printhead employs the cavities arranged in matrix form in trapezoidal zones with a width of a little over 1 inch. Oblique sides of each trapezoidal actuator unit are inclined and the actuator units are arranged close to each other as much as possible. This arrangement enabled to provide the printhead having a width of 22 mm.

At the same time, this design provides a structural continuity in the print width direction by a complementary arrangement of the actuators, cavities and nozzles leading from the cavities at the oblique boundaries of the trapezoidal actuator units facing each other. The arrangement can minimize a difference in print density at a boundary between the actuator units due to a difference in a quality of the actuator units, so that banding can not be recognized.

This design concept offers flexibility in the printhead design for requirements in the printing width. For example, it is possible to build a monolithic printhead with a print width of 8.5 inches by providing the actuator units on a substrate, in which channels are arranged in corresponding region, without increasing a depth. Even for such an expanded printhead, sufficient ink can be supplied through inlets, which can be increased in their number as a print width is increased since they are located at space beside shorter side of each actuator unit.

Forms of Cavities

Secondly, studies on cavity forms were conducted by computations to optimize their efficiency for compactness. It was assumed that conventional narrow cavities, as shown in Figure 6, might have less compliance so that they could not discharge ink for unimorph actuators because of their insufficient power. Also, such narrow cavities would require a certain amount of clearance between each of them in order to prevent crosstalk between neighboring cavities.

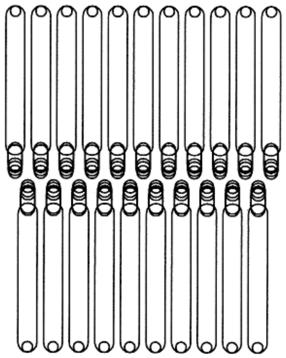
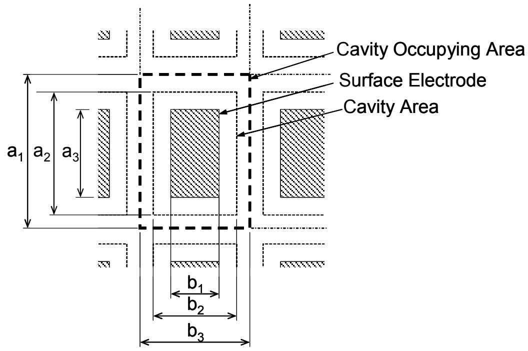


Figure 6. Narrow cavities of conventional printheads.

Figure 7 is a conceptual drawing showing a surface of a cavity model employed for series of calculations in this paper. In these calculations, a concept of a cavity occupying area, which is shown in Figure 7 as a region surrounded by thick broken lines, is introduced to evaluate the size efficiency in head design. The cavity occupying area is one of the equally divided regions of an imaginary matrix form that includes cavities and their surrounding walls.



a_1: Longer Side Length of a Cavity Occupying Area
a_2: Longer Side Length of a Cavity Area
a_3: Longer Side Length of a Surface Electrode
b_1: Shorter Side Length of a Cavity Occupying Area
b_2: Shorter Side Length of a Cavity Area
b_3: Shorter Side Length of a Surface Electrode

Figure 7. Conceptual surface view of cavity model.

In the calculations being discussed, rectangular models having different shapes and the same areas were used. They were different from each other in their aspect ratios of the cavity occupying area, cavity and surface electrode. Figure 8 shows calculation results on these models in volume change, magnitudes of crosstalk and compliances normalized by those of a rhombic model of the latest design against cavity aspect ratio. The results indicate that the cavity shape could influence on their functions of discharging ink even though dimensional, electrical and mechanical conditions are the same.

As the aspect ratio becomes closer to 1.0, the volume change of the cavity increases, the magnitudes of crosstalk decreases and the compliance increases. The conventional cavity structure with low aspect ratio has low compliance and good responsiveness to high frequencies. However, even if unimorph type actuators are applied to the conventional cavity structure, it will bring about little benefit because volume change will be small and magnitude of crosstalk will be large.

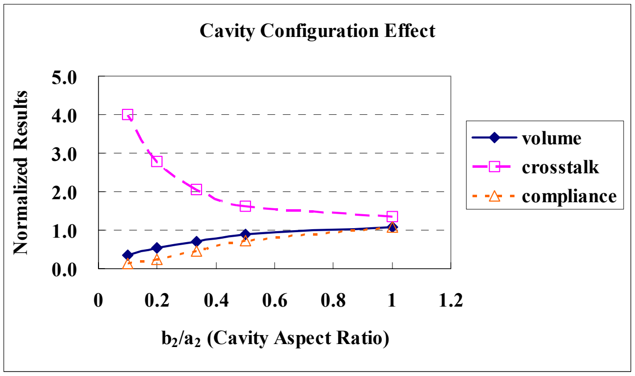


Figure 8. Effect of cavity form on mechanical properties to discharge Ink.

Mechanical Crosstalk

The actuator unit employs a simple flat structure consisting of plurality of piezoelectric ceramic layers, of which the top one involves a numbers of individual small active parts of unimorph actuators. However, this structure allows to transmit local strain of d31 mode generated at an active part to the neighboring active parts. They could suffer from the strain expanded in plain for vertical deformation towards cavities. It is how mechanical crosstalk occurs in the actuator unit being employed.

Effects of the crosstalk were evaluated by using a reduction rate of vertical displacement of an actuator unit due to the influence from neighboring active parts. These calculations were conducted on rectangular models whose cavity areas and aspect ratio of 1.0 were fixed but cavity occupying areas were varied. Also, effects of the crosstalk with a side active part (referred to an active part located on a side with facing its sides) as well as a diagonal active part (referred to an active part located in an extension of a diagonal line) were evaluated separately.

Figure 9 shows results of the calculations above against the cavity occupying area normalized by that of a rhombic model of the latest design. As shown in figure 9, the crosstalk rate dropped sharply when the cavity occupying area is smaller than 0.8, and the decreasing rate becomes gradual as the cavity occupying area becomes larger, in case of the crosstalk with a side active part especially.

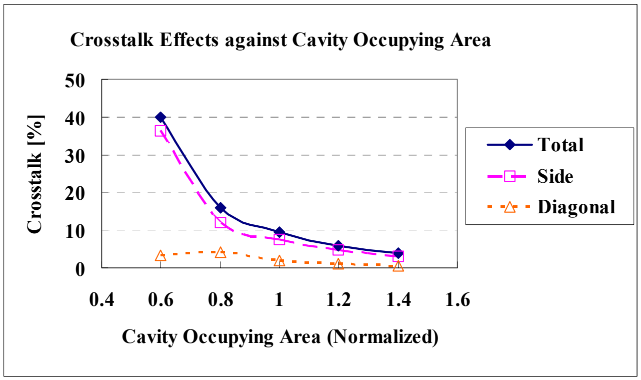


Figure 9. Comparisons of crosstalk rate in different directions.

The behavior shown in Figure 9 can be explained by the fact that an amount of inplane strain propagating along the piezoelectric ceramic layer from an electrode of the actuator, to which voltage is applied, to the surroundings decreases sharply as the distance from the electrode becomes longer.

Also, it is shown in Figure 9 that the mechanical crosstalk with a side active part is dominant whereas the effect of a diagonal active part is so limited. In case of the diagonal active part, the effect of the inplane strain is mainly gathered over the stiff area at the intersection of side walls surrounding the cavity. Therefore, the vertical deformation is restricted to small. In addition, the effect of the inplane strain is reduced by distance between active parts since they are relatively apart from each other in diagonal direction.

On the contrary, there is less constraint for the inplane strain between adjoining cavities (side active parts) because of wall structure having high compliance. Therefore, mechanical crosstalk with a side active part could have more impact on the volume change because of the insufficient constraint and the short distance from an active part.

Optimization in Cavity Forms and Configurations

On the basis of such elemental studies, the configurations of cavities were optimized to achieve the required volume change without exceeding the allowable level of crosstalk by a cavity having the smallest possible area. Numbers of cavity models were examined taking account of a positional relationship between the cavities and nozzles in terms of above objectives by using of a FEM program in the process of the optimization. The optimization process includes the steps as follows:

1. Rectangular cavities with aspect ratio of 1.0, which were the most effective ratio in deforming actuator units as discussed above, were arranged in square form
2. Cavity arrangement was changed so that adjoining cavities in the same rows could be lined in a direction diagonal to the row direction in order to reduce the mechanical crosstalk within a unit to be synchronized in their movement
3. A distance between the cavities facing by their sides was extended in order to reduce the mechanical crosstalk between the cavities located in the rows with respect to the diagonal direction
4. Each square cavity was transformed into a rhombic form, which is preferable in terms of fluid dynamics to purge air bubbles by a flow through them
5. The size of the cavities was adjusted to generate a required displacement in the actuator unit

The optimization was concluded by employing the latest arrangement (see Figure 10), in which sixteen rows of rhombic cavities were arranged in parallel to each other at a density equal to 37.5 dpi. This arrangement achieved to reduce the area occupied by a single cavity to 60% of the conventional ones while keeping the level of the mechanical crosstalk of equivalent to that of the conventional ones.

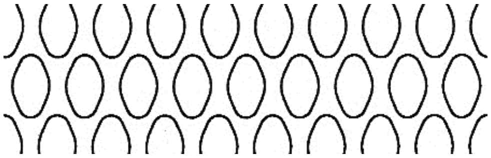


Figure 10. Forms and configurations of the latest cavities.

Piezoelectric Actuators Design

Outlines of Piezoelectric Actuators and Units of Them

Piezoelectric unimorph actuators were developed specially for the printhead. The actuator consists of two layered piezoelectric ceramic sheets, a common electrode layer disposed between them and an individual surface electrode. A group of actuators constitutes the trapezoidal actuator unit. Features of the actuator and the actuator unit are summarized as follows:

1. A large displacement can be generated by a fairly low voltage. In addition, power consumption for printing can be minimized due to small capacitance.
2. The individual surface electrodes, each of which defines a location and a region of each actuator, are accurate in their configuration since they are not inner elements sintered with other layers but formed on the surface after the unstable process.
3. The possible simplest structure is achieved.

These actuators have a laminated structure as mentioned above with 664 individual surface electrodes each of which corresponding to each cavity. In addition, several common leads, which are connected from the inner common electrode layer through the upper ceramic layer, are located at top and bottom sides of the trapezoidal actuator unit. Figure 11 shows a surface view of a piezoelectric actuator unit.

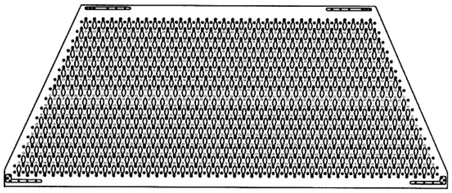


Figure 11. Piezoelectric actuator unit.

Optimizations in Layered Structure

The number of both active and inactive layers, thickness of each layer and width of the surface electrode, as well as material properties, such as piezoelectric constants, concern capabilities of a piezoelectric actuator to be employed in an inkjet printhead. Taking account of such elements, the actuator designs were examined by computations.

Diagrammatic cross sectional views and structural features of representative actuator models are presented in Figure 12 and Table 2, respectively. Displacements were obtained by calculations on the models with various thicknesses, in which each layer was equal in thickness.

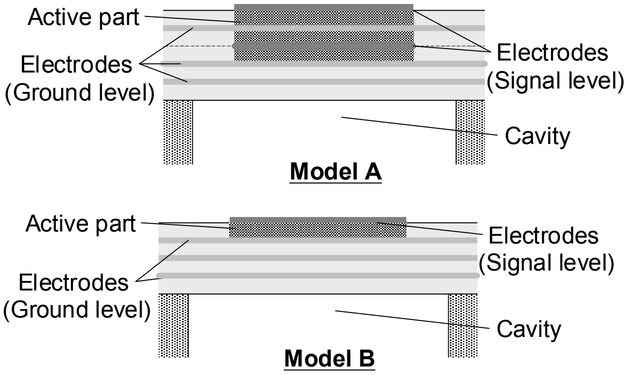


Figure 12. Cross sectional views of representative actuator models for simulations.

Table 2: Structures of Simulation Models

Model Type	Number of layers		
	Total	Active	Inactive
A	5	3	2
B	4	1	3
C	3	1	2
D	2	1	1

Figure 13 shows profiles of displacement at a fixed driving voltage against a thickness of each layer normalized with a cavity width. The thickness of the layer is represented by T_L and the cavity width is represented by W_C. Also, displacements are normalized by displacement of model A, when the normalized layer thickness of the model A is 0.034.

The figure shows that displacement of the actuator in each model decreases sharply as each layer becomes thicker. It can be assumed that the displacement is influenced by increases in both compliance and magnitude of electric field due to decrease in thickness of each layer.

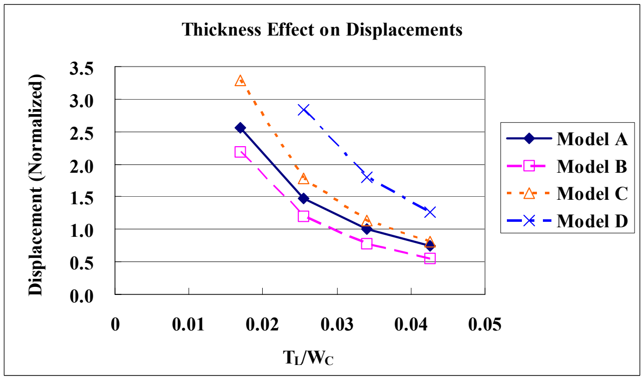


Figure 13. Effect of thickness in layered structures on actuators displacement.

The displacement profile of model A does not show outstanding superiority to the models with single active layer in deformability in spite of its triple active layers due to an effect of incompliance given by the thickness. Moreover, it is considered that inner active layers do not make so much contribution to vertical deformation as the top layer does in a unimorph actuator with multiple active layers.

Comparing displacement profiles between models B, C and D, of which active layer is single, the model with the fewer number of inactive layers deformed more as shown in the figure. It is also due to increase in compliance by decrease in thickness. However, actuators, with too much compliance, that are made up of the small number of thin layers could be forced back by compressed ink filled in cavities.

In addition to above results, compliances were obtained by computations to compare these models in terms of efficiency for discharging ink.

Figure 14 shows profiles of displacement against normalized compliance. It clarifies excellence of model A in deformability compared with the other models with single active layer.

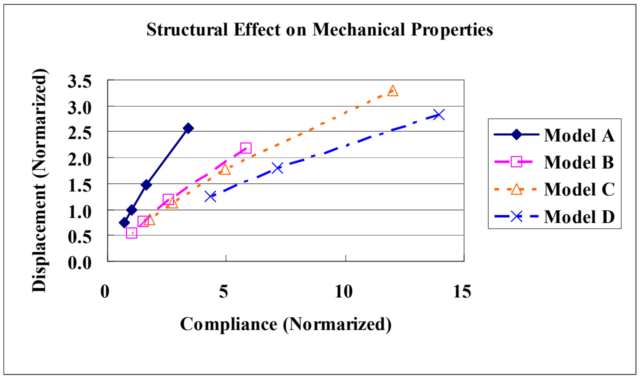


Figure 14. Effect of compliances in layered structures on actuators displacement.

The results suggest that the thinnest model, i.e. the model D, need to have compliance 3 times as high as that of the model A to obtain equal displacement. Although decrease in stiffness of the cavity due to such an increase in compliance is not negligible relatively to bulk modulus of ink filled in the cavity, it is assumed that it would not make so much loss in the displacement caused by the repulsive force.

Taking account of these results, actuators with single active layer were examined on printheads as discussed below.

Optimization by Experiments

Actuators corresponding model B, C and D with different thickness in each layer were examined in the printheads. Figure 15 shows representative results of driving voltage and displacements to attain average droplet velocity of 9 m/s by printheads of the latest design. The droplets velocities were measured with inks of 3.2 mPa*s viscosity at 1 mm from nozzles.

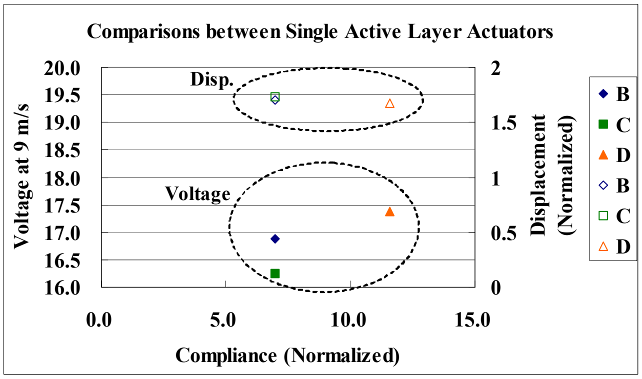


Figure 15. Comparisons between single active layer Actuators

It is shown in figure 15 that all the actuators are driven at relatively low voltage for achieving droplet velocity of 9 m/s. The actuators with single active layer are thus verified.

Although compliances are different among the actuators, displacements required for the actuators to achieve the velocity are almost equal in the results. Moreover, trend of displacement against compliance agree with that predicted by computations. It suggests that a displacement loss due to the actuator compliance and the repulsive force is not effective in conditions being discussed as it is assumed.

The actuator corresponding to the model D requires slightly higher voltage than that of the other actuators. However, it consumes the least power, 2.5 mW/nozzle in typical conditions, because of the lowest capacitance by the thickest active layer among these actuators.

As a result, it is concluded that the possible simplest unimorph actuator consisting of two layers is suitable to be employed for the printhead since it is the most preferable structure in terms of the efficiency as well as productivity.

Printing Capabilities

Single Pass Printing

The printhead was designed and optimized for single pass printing, which requires uniformity in firing quality among the nozzles. As it is known, droplet velocities and droplet placement accuracy are appropriate indexes to evaluate firing quality. Figure 16 shows an example of a droplet velocity distribution in 160 out of 2,656 nozzles along print width direction. Also, Figure 17 shows droplet placement accuracy along print width direction measured for 480 nozzles in 3 rows.

Figure 18 shows magnified view of a color image printed by using 6 of printheads at paper feeding rate of 840 mm/sec. As shown in Figure 18, the developed printhead attained a quality of practical photographic level by single pass printing.

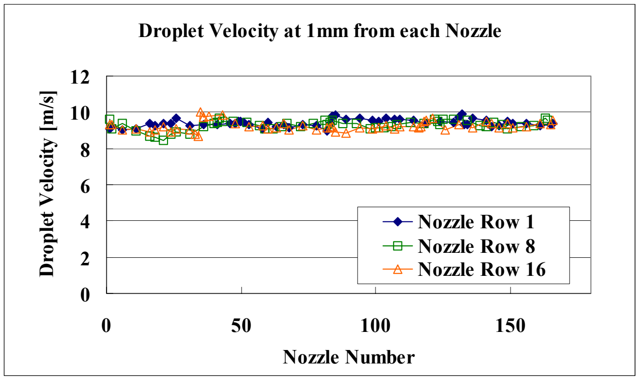


Figure 16. Droplet velocity distribution in print width

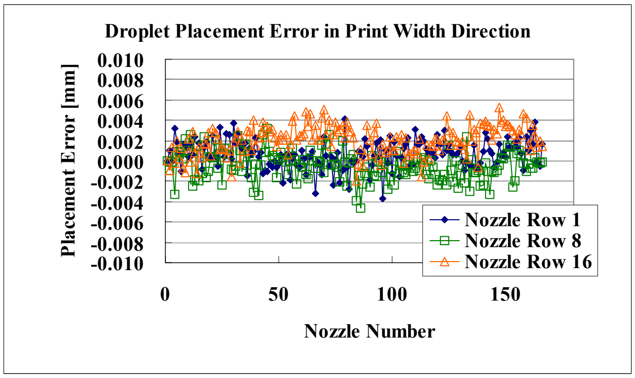


Figure 17. Droplet placement accuracy in print width

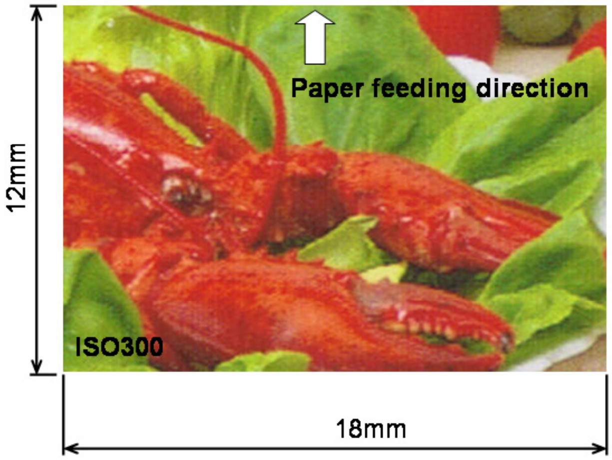


Figure 18. Magnified view of image printed with resolution of 600 x 600 dpi in single pass method by using developed printheads.(ISO/DIS 12640 N5A)

Conclusion

Drop-on-demand monolithic piezoelectric line inkjet printheads with print width of 108 mm were built. It achieved firing rate of 20 kHz, or printing speed up to 840 mm/s at a resolution of 600 x 600 dpi.

A printhead design with compact structure, low driving voltage and small power consumption was achieved by optimizing arrangement of pressure chambers and actuators consisting of two layered piezoelectric ceramic sheets without suffering from too much crosstalk. There are 2,656 nozzles in the front end unit, of which width, depth and height were 152, 22 and 1 mm respectively. The printhead design can be applicable to various printing sizes and materials by an extendable structure and anticorrosive components employed in the printhead.

The printhead was built up of thin plates, in each of which nozzles and groups of channels were formed. This structure makes dimensional accuracy of each component of the printhead high. Therefore, ink-ejection performance of the printhead is uniformed and high image quality can be realized. In addition, the structure makes a contribution to a printer design for its compactness. As a result, quality of printed images was verified as a practical photographic level.

References

1. Y. Ohta, “J. Imaging. Sci. of Japan, 43, 480 (2004).
2. K. Nakajima, “J. Imaging. Sci. of Japan, 43, 473 (2004).

Author Biographies

Atsushi Hirota received his B.S. degree in mechanical engineering from Kyoto University (1986). In 1986, he joined Brother Industries, Ltd., where he's consistently been engaged in the development of printheads. He has designed impact-dot printheads from 1986 to 1995, and inkjet printheads since 1995. He is currently a manager of Printing Research & Development Dept.

Shin Ishikura joined Kyocera Corporation in 1995. Since then, he has been pursuing development of printheads and their components. He received his degrees of M.S. and M.Eng. from Liverpool John Moores University and Kanazawa University respectively. His interest lies in the mechanical phenomena occurring in printheads.