Improvement in Printing Throughput for Piezoelectric Line Ink Jet Print Head

Ishikura, Shin/ Matsumoto, Ayumu; Kyocera Corp., Kirishima, Kagoshima, Japan

Abstract

In the past two years, one of the authors published development and analyses works as to a drop on demand piezoelectric line ink jet print head. The print head is composed of a monolithic structure having resolution of 600 dpi in 108 mm print width. It is provided with 2,656 nozzles with corresponding pressure chambers, or cavities, in an area of 108 x 16.8 mm. This print head was originally designed to generate drops of 3 /7 /14 /21 pL at 20 kHz firing frequency for 600 x 600 dpi 4 grades grayscale printing at paper feeding rate of 847 mm/s. The authors have expanded its capability in firing frequency to 24 kHz with 3 / 7 /9 /12 pL drops. The higher frequency allows printing rate of 1,016 mm/s for paper feeding in the same resolution. In general, the faster printing requires more unity in drop formation to make pixels on a substrate shaped finely, which is inadequate for the original design. Therefore, modifications are made with the print head in its actuator and a cavity structure in order to unify drops for each pixel more consistently. Specifically, unimorph actuator thickness, cavity shape and depth are examined so that residual vibration in a channel might not break up a ligature during drop formation. As a result, the print head is improved in its printing speed as referred above.

Introduction

Thank for personal digitalization given by PCs and digital cameras, ink jet technology has expanded its markets mainly in consumer and wide format printing applications in past decade. Not only in quantity, but also it has made progress in terms of printing quality and speed by such technical approaches as decrease in drop volume, increase in numbers of nozzles, grayscale levels and colors [1].

However, in spite of the achievement, ink jet technology still has not played important role yet neither in offices nor printing industries, in which large amount of document is treated. It has been explained by narrow tolerance for ink and substrate types or instable performance due to accidental nozzle clogging. Moreover, it could be arisen incompatibility of productivity with printing quality at acceptable level for industrial purposes.

In order to make a breakthrough, it is natural to come up with a concept of high resolution single pass printing. Historically, Canon realized the first drop on demand line ink jet print head in '80s with their thermal jet technology. Commercially, continuous print head technology, which was developed by Scitex and succeeded to Kodak, had established dominant position in data print market through '90s.

However, the situation has been changing rapidly in a few years. There are single pass ink jet printers for both office and commercial printing markets such as ORPHIS by Riso, Edgeline by HP, True Press by Screen and MJP600 by Miyakoshi. In addition, Canon[2], Silverbrook[3], Xaar[4] and Fuji Xerox[5] published their line head technologies. These are distinguished from the old generation by their print quality obtained from higher single pass resolutions or grayscale levels.

Also, as reported in previous papers, Kyocera developed 4" line ink jet print head with Brother Industries, LTD. [6]. This print head achieved single pass print throughput of 847 mm/s with 5 levels gray scale by 20 kHz firing frequency.

There is also improvement in the market environment to utilize benefits of single pass ink jet technologies for small lot or variable data printing with acceptable image quality.

Having expected a demand for even faster printing on coated plain paper, like a transaction printing market, Kyocera has improved their print head in its throughput. As a general concept, it is modified in fire frequency from 20 kHz to 24 kHz with 4 levels grayscale. The maximum drop volume is reduced to 12 pL, which is enough to assure full coverage on a substrate of this kind. Representative specifications of the modified print head are summarized in table 1. Also, figure 1 shows its appearance.

This paper summarizes technical subjects and approaches in design optimizations, through which the authors have achieved the specified printing speed.

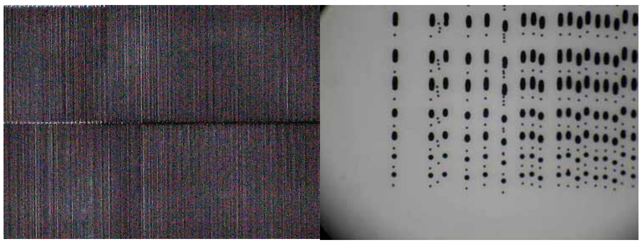
Table **1: Representative Specifications of the Print Head**

1. Dimension	200(W) x 25(D) x 60(H) mm
2. Number of Nozzles	2,656 nozzles per head
3. Print width	108 mm (4.25 inches)
4. Resolution	600dpi (print width direction)
5. Drive frequency	Up to 24 kHz

Figure 1. *Appearance of the print head.*

Subjects with Original Design

Initially, by using the original print head, authors tried printings with resolution of 600 dpi in paper feeding direction at 28 kHz firing frequency, which correspond to 1,185 mm/s feeding rate. Figure 2 shows magnified views of the prints, of which the density variation was appeared to be periodical misfiring whereas regular noise was generated by instable meniscus behavior. From mechanical view point, it was assumed that insufficient or inappropriate acoustic response within a discharging unit, which includes an individual channel from a restrictor to nozzle and unimorph actuator as shown in figure 3, had influenced the phenomenon.



(a) Density Variation *(b) Regular Noise*

Figure 2. *Failures on print samples with original print head.*

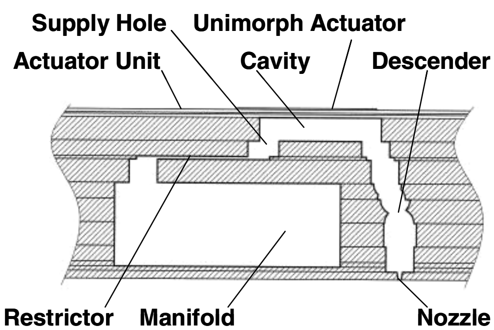


Figure 3. *Cross sectional view of discharging unit.*

In case of a bend mode print head like this, unimorph actuator could be the most compliant element within a discharging unit. Therefore, optimization of actuator and cavity configurations are taken into consideration to improve the response firstly.

Also, as one of the authors reported last year, there are residual oscillations of two different acoustic modes at least in a discharging unit, which could be influential for occurrence of satellites [7]. These satellites could not have been identified on images printed at 20 kHz firing, or paper feeding rate at 847 mm/s, since they dropped on main dots precedent to them. However, faster paper feed could place them on a substrate individually.

In terms of pressurizing efficiency at drop formation, it is preferable to make a ratio of acoustic periods of the primary to the second modes about 5.0 as referred in previous study [7]. In order to attain acoustic system as such, cavity and actuator dimensions have to be taken into account since they have much impact on the both resonances.

Process of Design Optimization

Reduction in Actuator Compliance

Having taken the discussions above into consideration, cavity and actuator designs are optimized in terms of better response, or smaller compliance, as well as synchronization of the primary and second mode resonances for drop unity.

Firstly, actuator design is investigated with a commercial FEM program to optimize actuator thickness and width that defines constraints on actuator bending. Dimensional features of investigated models normalized with the original are summarized in table 2. By the series of calculations, it is aimed to search actuator designs that assure at least 80% of original displacement in a cavity, which is minimum volume change compensatable with the driver circuit.

Table **2: Normalized Dimensional Features of Actuator Models**

Mode l	Cavity Width	Act. Thickness
A-1	0.97	1.00
A-2	0.97	1.05
A-3	0.97	1.10
B-1	1.00	1.00
B-2	1.00	1.05
B-3	1.00	1.10
C-1	1.02	1.05
C-2	1.02	1.10
C-3	1.02	1.15
D-1	1.05	1.05
D-2	1.05	1.10
D-3	1.05	1.15
E-1	1.10	1.10
E-2	1.10	1.15
E-3	1.10	1.20
F-1	1.12	1.10
F-2	1.12	1.15
F-3	1.12	1.20

Figure 5 shows trend of actuator displacement against compliance relative to that of original design B-1. Generally, the displacement increases linearly against compliance in spite of difference in cavity shapes. Of these results, displacements taken by actuator models A-2, B-3, C-3, D-3 and E-2 exceed allowable minimum level with relatively small compliances.

Also, these actuator models are evaluated in their efficiency, or pressurizing constant, which could be defined with pressure increase per applied voltage as expressed in equation (1) below. It is shown in figure 6 that model E-2 is the most efficient one among the actuator models mentioned above. From practical view point, model E-2 is selected for further examinations because of its small compliance compatible with efficiency.

$$K_P = \frac{\delta S}{C_a \cdot V} \tag{1}$$

Kp: Pressurizing Constant
δS: Displacement in a cavity space by an applied voltage
C_a: Acoustic compliance of a unimorph actuator
V: Applied voltage

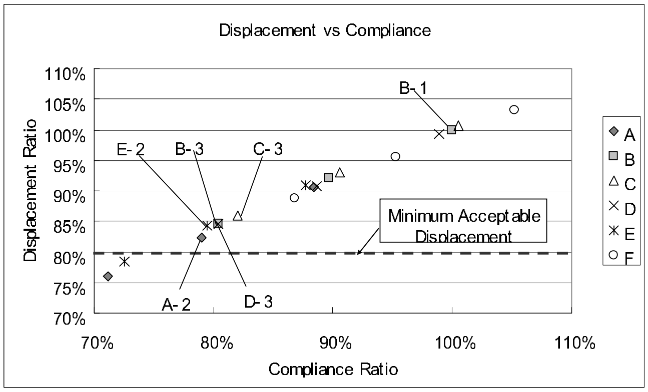


__Figure 5.__ Normalized compliances against actuator thickness.

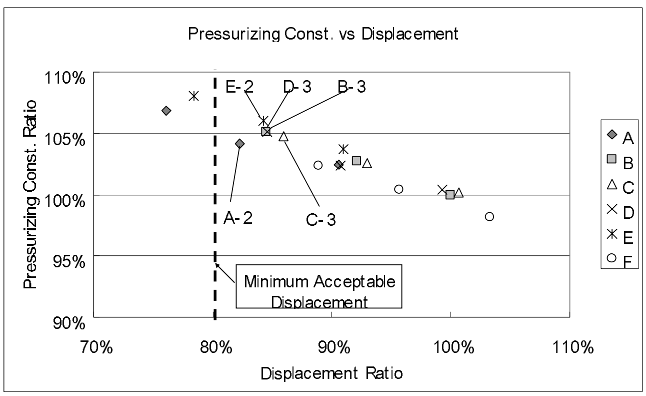


__Figure 6.__ Pressurizing constant ratio against displacement ratio.

Optimization in Acoustic Resonances

Then, the primary and second mode acoustic periods are calculated for discharging units with actuator model E-2. As discussed in previous report, these periods are expressed as equations (2) and (3) respectively [7]. And, figure 7 summarizes trends of the acoustic periods ratio mentioned above against cavity depth normalized with original design. As shown in figure 7, the acoustic period ratio closes to 5.0 with cavity thickness range between 0.5 and 0.8.

$$T_C = 2\pi\sqrt{\left(\frac{M'_n \cdot M'_r}{M'_n + M'_r}\right)\cdot\left(C_a + C_c + C_s + C_d\right)} \qquad (2)$$

$$M'_n = M_n + M_c/2$$

$$M'_r = M_r + M_c/2$$

T_C: Acoustic period of a discharging unit
M_n: Acoustic inertance of a nozzle
M_r: Acoustic inertance of a restrictor
M_c: Acoustic inertance of a cavity
C_c: Acoustic compliance of a cavity
C_s: Acoustic compliance of a supply hole
C_d: Acoustic compliance of a descender

$$T_S = 2\pi\sqrt{\left(\frac{M_d \times (M_c + M_s)}{M_d + M_c + M_s} + M_a\right)\cdot\frac{C_d \times C_a}{C_d + C_a}} \qquad (3)$$

T_S: Acoustic period of the second resonance
M_d: Acoustic inertance of a descender
M_a: Acoustic inertance of an actuator
M_s: Acoustic inertance of a supply hole

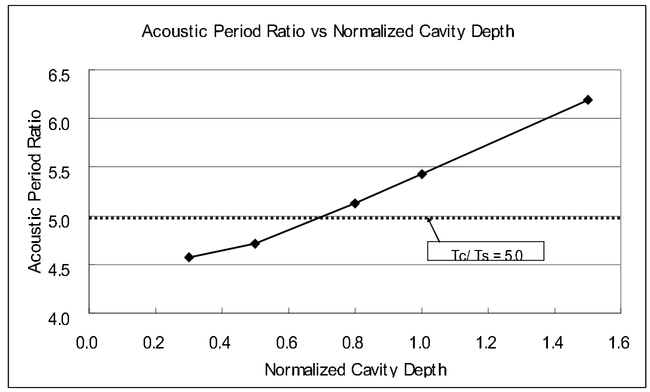


__Figure 7.__ Acoustic periods ratio against normalized cavity depth.

Experiments on Print Heads

On basis of numerical studies above, print heads with actuator design taking structure of model E-2 with normalized cavity thickness 0.3, 0.5 and 0.8 are manufactured for experiments. These print heads are to be called in this report as E-2-1, E-2-2 and E-2-3 respectively. Of these print heads, E-2-1 is examined rather for confirmation of validity of the numerical assumption above.

Firstly, these print heads are compared in drop formation by using a test rig equipped with a strobe, CCD camera and magnifying optical apparatus. Secondly, the best one in terms of drop unity is applied to printing.

Drop Form Observation

For the print heads mentioned above, drop forms are observed at a fixed timing after applying a driving signal to an actuator as shown in figure 8.

Figure 9 shows drop forms of each print heads against switching interval from 4.0 to 8.0 μs at 0.2 μs steps although drops could not be observed at 8.0 μs in case of E-2-1. Also, distance between a drop and nozzle plate in this figure indicate the velocity.

In case of print head E-2-1, leading drop positions trace rather flat velocity profiles. In addition, drops are separated in various shapes as switching interval increases. It could be explained as a result of mismatched phases in acoustic oscillations.

On the other hand, print head E-2-3 shows single clear peak in the leading drops profile although their followers are left behind in plural tips. In case of the drop form like this, synchronization of acoustic oscillations in a channel might have accelerated the meniscus at initial stage of drop formation. After then, oscillation of the shorter period would divide the drop by reversing its phase preceding the primary acoustic oscillation of longer period.

However, print head E-2-2 shows different aspects in terms of drop unity. There are flat twin peaks in leading drop profile that suggest existence of difference between phases of the primary and second modes acoustic oscillations. As shown in the figure, leading drops and followers are rather close between these peaks, which suggest that the leading drop is slowed down due to the slight gap in phases of the acoustic oscillations. As a result, print head E-2-2, which might have been in the medium status between the other two print heads, is selected for the print test.

Then, driving signal wave forms are optimized for the specified drop volumes. Figure 10 shows drops of various volumes discharged with print head E-2-2 by the optimized driving signal wave form. As shown in the figure, drops are unified regardless of the volumes.

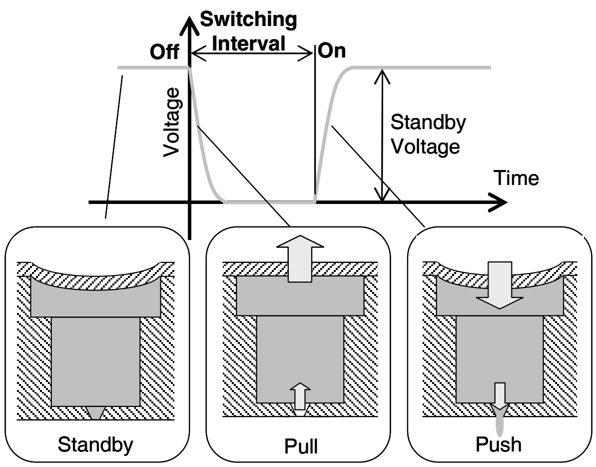
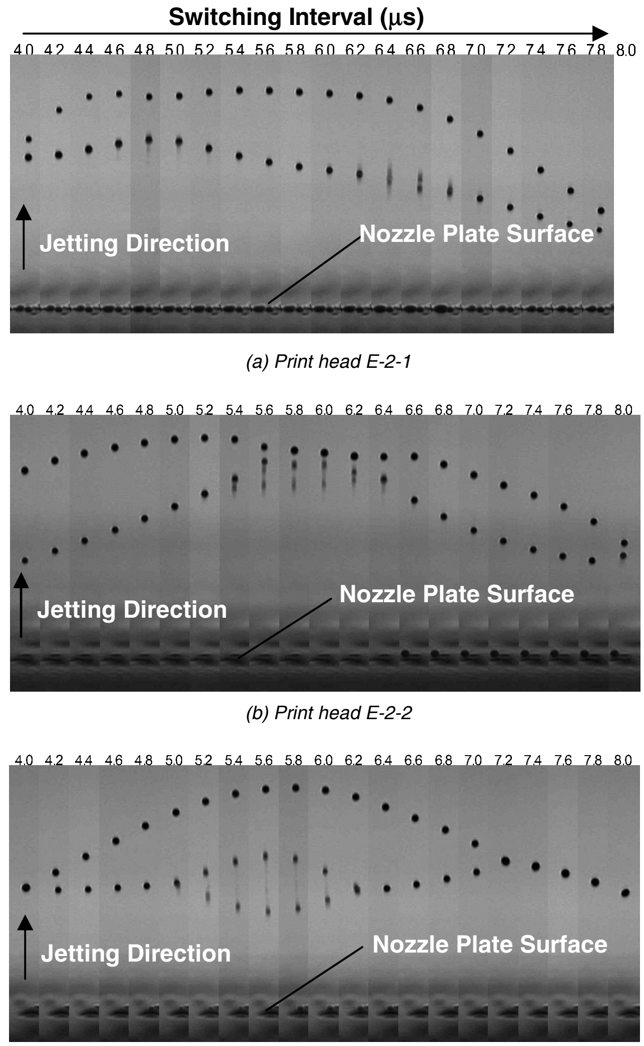


Figure 8. *Notion of a driving signal.*

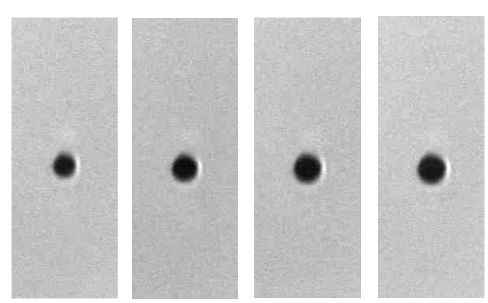


(a) Print head E-2-1

(b) Print head E-2-2

(c) Print head E-2-3

Figure 9. *Normalized compliances against actuator thickness.*



3pL *7pL* *9pL* *12pL*

Figure 10. *Optimized drop forms of various volumes fired at 24 kHz.*

Print Test

Then, print head E-2-2 is examined for printing with the optimized driving signal on a single pass flat table printer. Figure 10 and 11 show magnified view of the prints, which are printed on glossy paper and coated plain paper with 1.0 mm gap between the substrates and nozzle plate at paper feeding rate of 1,016 mm/s. It is shown in the prints that neither regular noise due to satellites nor density variation by misfiring exists any longer.

Conclusion

Mechanical designs are studied on a piezoelectric line ink jet print head to improve the printing throughput.

Firstly, the unimorph actuator design is investigated to improve its response without spoiling its deformability. A commercial FEM program is used for the study.

Secondly, cavity design is examined in terms of acoustic characteristics to synchronize oscillations in a discharging unit at timing of a compression. The primary and second mode acoustic periods are calculated with equations proposed by one of the authors.

Thirdly, drop forms are observed on print heads, which are designed on basis of the studies above. One of the print heads shows fairly good unity in drop forms.

Finally, the optimized print head is confirmed its printing capability at paper feeding rate of 1,016 mm/s, which exceeds the original specification.

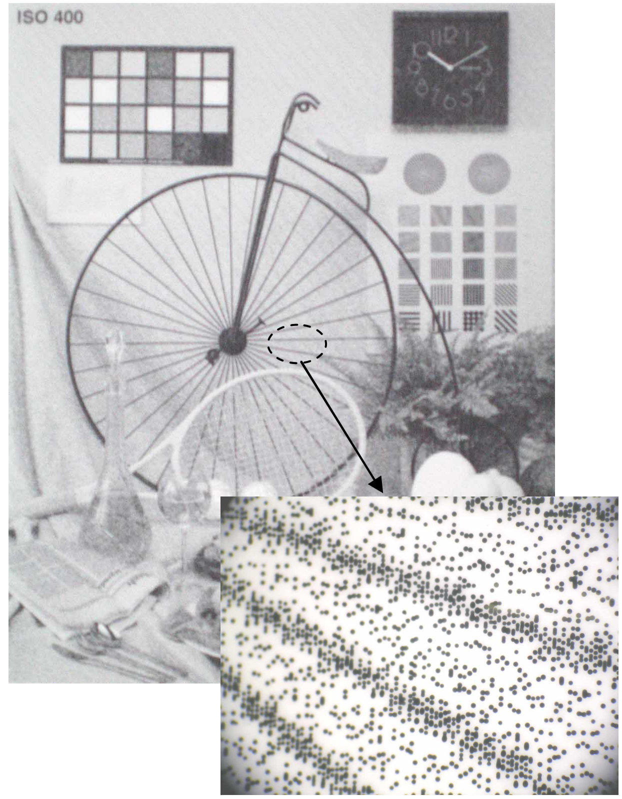


***Figure** 11. Magnified view of print samples on glossy paper.*

References

[1] K. Nakajima, "Inkjet Technologies 2004", Journal of the Imaging Society of Japan, 43, p473 - 479 (2004).

[2] E. Motai, M. Toriumi, "Photo-quality printing by the stationary wide print head system", Proc. ICJ, IST, (2006).

[3] http://www.memjet.com

[4] http://www.xaar.co.uk

[5] S. Seto, S. Umehara, M. Kataoka, M. Okuda, "Full-Width-Array Piezo Inkjet Printhead using Matrix Nozzle Arrangement", Proc. ICJ, ISJ, p125 - 128 (2007)

[6] A. Hirota, S. Ishikura, "Development of Drop - on - Demand Piezoelectric Line Inkjet Printhead", Proc. NIP21, IS&T, p257 - 263 (2005).

[7] S. Ishikura, M. Hibi, "Acoustic Analyses on Oscillatory Behaviors in Piezoelectric Ink Jet Printhead", Proc. NIP22, IS&T, p75 - 78 (2006).

***Figure** 12. Magnified view of print samples on glossy paper.*

Author Biography

Shin Ishikura joined Kyocera Corporation in 1995. Since then, he has been in development section for print heads and their components. He received his degrees of M.S. and M.Eng. from Liverpool John Moores University and Kanazawa University respectively.

Ayumu Matsumoto was given his B.Eng. degree in mechanical engineering from Kagoshima University in 1996. He joined Kyocera Corporation in 1998 and started his career as a print head designer in 2002.