Dynamics of Piezoelectric Inkjet Printing Systems

Shinri Sakai
SEIKO EPSON Corporation
Shiojiri, Nagano, Japan

Abstract

In recent years, the inkjet technology has made great strides in the print quality. By introducing fine droplets, deep and light color inks, optimized media, and advanced color and image processing, the latest inkjet printers can produce photo-quality prints. Of these many improvements, the most contributive one is that the innovative piezoelectric print head has reduced the ink droplet size by a factor of ten in the latest five years. This innovation has been accomplished by optimizing head dimensions and driving signals as well as improving the manufacturing and assembling process. The piezoelectric actuator driven by the signal, optimized for the particular print head model, can precisely control the unrestrained ink meniscus vibration at the nozzle openings to achieve multi-sized droplets ejection in a sequent manner as well as stabilized droplet ejection up to the extremely high ejection repetition frequency. This Variable-Sized Droplet Technology (VSDT) has made it possible to introduce the digital photo-printers to the market without trading off the throughput. This paper shows how the piezoelectric inkjet technology has been improved and how much flexibility it has for particular use in home, office and industry.

Introduction

Today, the inkjet technology has made it possible to produce high quality digital photo prints that compete against the silver halide photographs by the cooperation between the improvements of the components that constitute the inkjet technology [1] and to extend its application to wide and pioneering area by its compatibility and flexibility with digital sources.

Two types of the inkjet head technologies, one is using piezoelectric actuators and the other is using heater elements, are well known in the market. Because they have different physics and mechanism, they also have been taking different approaches to producing fine droplets. Figure 1 shows the history of the ink droplet size reduction achieved by the EPSON's inkjet printers since its first market model in 1984. Throughout the evolution of the piezoelectric print heads, EPSON faced several difficulties in the development. Two innovative MACH technologies broke through the difficulties in 1992 and 1995 and made it possible to continue to make the successful progress. As is shown in Figure 1, the minimum droplet volume has been reduced every year and now reached 3pl. This rapid and drastic evolution, that reduced the ink droplet size by the factor of ten in the latest five years and still continues, have been making revolutions in the printing technology.

This paper will describe the structure of the inkjet heads, the dynamics of the heads, the basic approaches to generating fine droplets, and the multi-sized droplet technology accomplished by precisely controlling ink motion of the EPSON's piezo-type inkjet printers. The application area of the piezo-type head will also be mentioned.

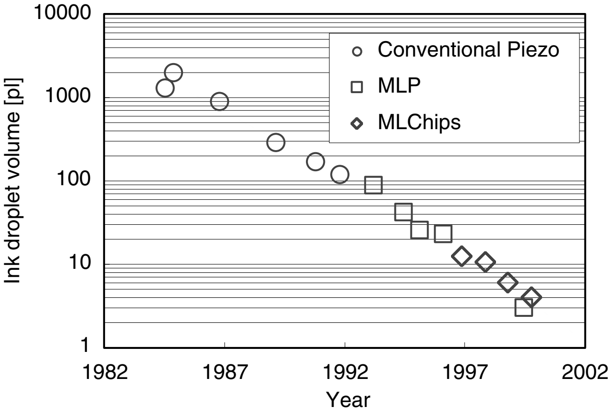

Figure 1. History of ink droplet volume of EPSON's piezo type printers.

Structure of the Piezoelectric Print Head

The piezoelectric inkjet head has a mechanism that transfers piezostriction to a volume change of the pressure chamber and this volume change induces oscillating ink flow that generates droplets from a nozzle opening. There are several types of the piezoelectric inkjet heads in terms of the mechanism of the piezo transducer.

Conventional Piezo Head

The early models since 1984 used piezo transducers similar to the head in the reference [2]. Each pressure chamber, sealed by a thin elastic plate, has a piezo strip that is narrower than the chamber width. The unimorph actuator (or vibration plate), composed of the laminate of the piezo strip and the elastic plate, transfers piezostriction to flexural deformation of the vibration plate. Figure 2 shows a plane view of the head of this type. The nozzles in a line are connected to the pressure chambers placed with large space by the long and winding channels. The manufacturing process, that puts and glues the each piezo strip on the channel substrate of plastic or glass, restricts the use of thin piezo elements thinner than about 100µm, because the piezo material is very brittle and easy to break in the process. As described later, this dimensional restriction limits the reduction of the droplets and the heads.

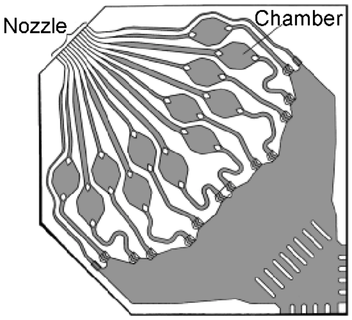

Figure 2. Conventional Piezo Head.

MLP (Multi-Layer Piezo) type MACH

To break through this limitation, EPSON developed new inkjet head with multi-layer piezo actuators called MLP type MACH (Multi-layer ACtuator Head), and introduced new printer with MACH in 1992 [3]. The MLP type MACH, shown in Figure 3, has multi-layer piezo elements sliced to thin pillar shape, one end of them is fixed to the base and the other end is connected to the vibration plates of the pressure chambers. This piezo element gets shorter to extend the pressure chamber by the transverse piezoelectric effect when voltage is supplied. Beside the unimorph actuator, the MLP actuator can transfer the piezostriction directly to the displacement of the vibration plate regardless of the pressure chamber size.

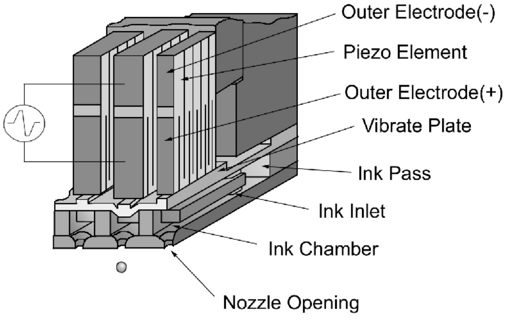

Figure 3. Structure of the MLP type MACH

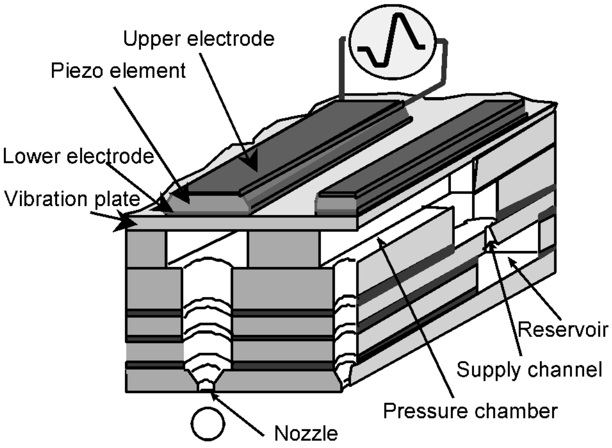

Figure 4. Structure of MLChips type MACH.

MLChips (Multi-Layer Ceramic with Hyper Integrated Piezo Segments) type MACH

While having high performance, the MLP type MACH costs a lot to be manufactured. To meet the market demand for low-cost and high performance inkjet printers, EPSON developed another MACH in 1995 [4]. Though the principle of the transducer, shown in Figure 4, is similar to the conventional piezo head, the piezo strips are not independently manufactured but processed and sintered together with the flow channel substrate as a single layered ceramics structure. As described later, it is strongly required to make both of the vibration plate and the piezo strip thinner to improve the inkjet head for jetting fine droplets. By taking the process that unifies the core parts of the head without machining and gluing, the MLChips could break the barrier, which the conventional piezo heads had, to develop the high cost performance printers by reducing the head dimensions.

Dynamics of the Print Head

Understanding the motion of the actuator and the ensuing ink flow, which are actually coupled each other, and precisely estimating the parameters that define and characterize the motion, the accurate design can be done to meet the fine droplet target. In this section, the basic analytical models for the estimation of the inkjet head's response will be explained and the responses to the simple basic inputs will be shown. Then, the relations between the analytical models and design parameters, and the strategies to the design for generating micro droplets will be described.

Analytical models for the piezoelectric inkjet heads

The channel flows that interact with the actuator as inkjet heads do are well explained by the acoustic model that takes volume velocity and pressure as independent variables. Each component of the inkjet head, such as nozzle, pressure chamber, and vibration plate, is expressed in terms of acoustic impedance, composed of inertance, compliance and acoustic resistance, and is put together in electric circuit as a equivalent model of the inkjet system.

Figure 5 shows the simple equivalent circuit model for the MLChips type MACH, which uses unimorph actuator, and two major vibration modes. The mode in Figure 5(b) is the vibration mode of the pressure chamber connected to the compliance of the chamber that results in ink droplet ejection from the nozzle. The mode in Figure 5(c) is the vibration mode of the ink supply flow connected to the capillary force at the nozzle meniscus that manages the frequency characteristics of the droplet ejection.

Figure 6 shows the equivalent circuit model for the MLP type MACH. The longitudinal vibration actuator of MLP has high rigidity and can actuate the vibration plate forcibly. Add to the vibration modes of the pressure chamber (Figure 6(a)) and the ink supply flow (Figure 6(b)), there is the vibration mode of the MLP (Figure 6(c)).

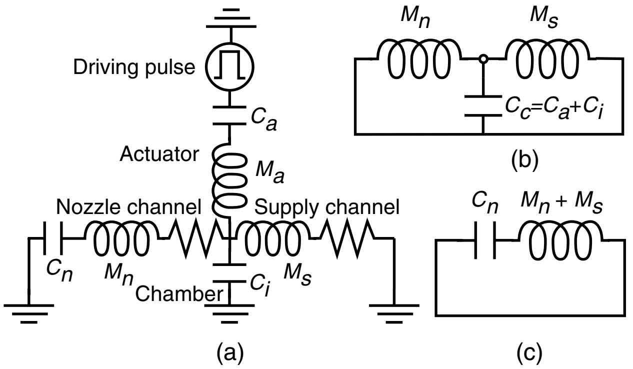

Figure 5. Equivalent model of the MLChip type MACH.

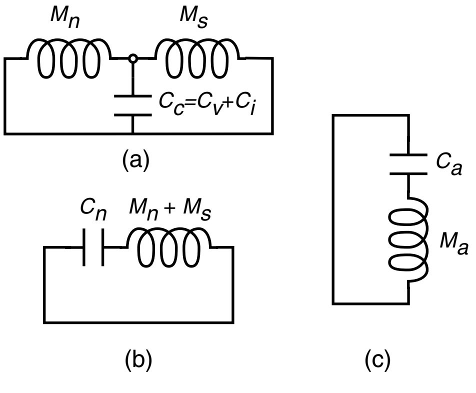

Figure 6. Equivalent model of the MLP type MACH.

Meniscus control

When a drive signal is applied to the piezo element, induced piezoelectric strain generates a driving force and excites the above mentioned vibration modes. Of these vibrations, the mode of the pressure chamber and its oscillation period T_c determine the characteristics of ink ejection. Figure 7 shows the oscillating flow at the nozzle of MLChips type MACH connected to the vibration mode of the pressure chamber in response to a drive pulse of which width is the same as the oscillation period T_c. Figure 8 shows the response to a negative drive pulse of which width is half of the T_c.

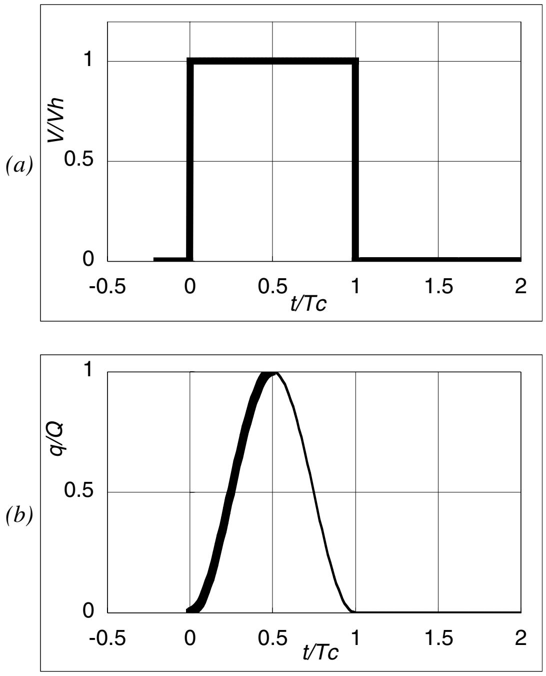

Figure 7. Push-Pull pulse (a) and response (b). Time in abscissa is normalized by Tc, and also voltage and flow quantity in ordinates are normalized by the pulse height and flow amplitude respectively.

The drive pulse shown in Figure 7 excites the ink oscillation that flows outward first at the preceding positive edge of the pulse, and pushes the ink at nozzle to generate a droplet. The following edge of the pulse excites the ink oscillation that flows inward first. As the following flow is in opposite phase to the preceding flow, i.e. out of phase, both flows cancel each other and no oscillation flow remains. This driving method is called Push-Pull operation.

In the case of the drive pulse shown in Figure 8, the pulse width of that is half of the T_c, an ink flow excited by the preceding pulse (negative) edge starts to draw ink meniscus inward first, and at the time just when the ink flow begins to turn its flow direction, the following edge of the pulse generates another ink flow. Because these two ink oscillation flows are in phase, they reinforce each other, then construct a large oscillation flow, and generate a droplet twice as fast as the Push-Pull operation. This driving method is called Pull-Push operation.

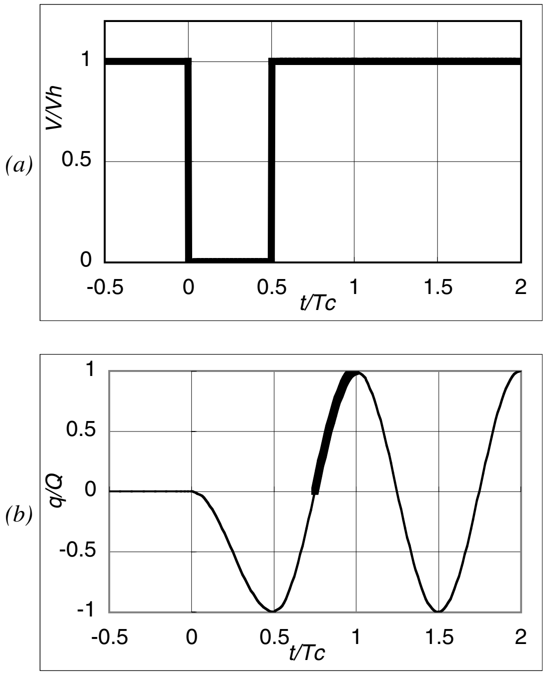

Figure 8. Pull-Push pulse (a) and response (b).

As well as the pulse width described above, rise-time or fall-time, in that time the pulse ramps up or down between two voltages, is also very important parameter. Compared with the sharp edge case, if the rise-time or fall-time is equal to the T_c, no overshoot is observed in Figure 9. This pulse edge draws ink meniscus to some amount without any residual oscillations and is very useful for precise meniscus control.

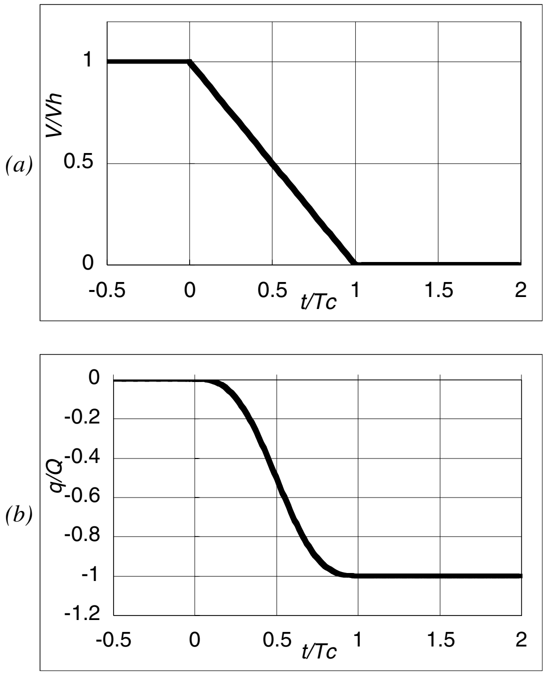

Figure 9. Ramp step input (a) and response (b).

Approach to fine droplets generation

Generally, reducing the droplet volume causes slowing down the droplet speed. In the shuttle type inkjet printers, the inkjet head ejects droplets while moving fast, so the slower droplets degrade dots positioning accuracy and resultant image quality. Accordingly, the way to the faster droplets is exactly the way to the smaller droplets.

The droplet velocity is estimated by integrating ink momentum going out of the nozzle and then dividing the figure of the momentum by the droplet mass. In the case of the Push-Pull operation, integrating the flow, thick line in Figure 7, gets the droplet velocity V_m as

$$V_m = \frac{\pi^2}{4} \frac{Q}{T_c A} \tag{1}$$

where Q is the droplet volume and A is the area of the nozzle aperture. And the oscillation period T_c is

$$T_c = 2\pi \sqrt{M C_c} \tag{2}$$

where C_c is the compliance of the pressure chamber and M is total inertance of parallel connection of the nozzle and supply ink channels.

From Equation (1), the smaller the oscillation period T_c and nozzle become, the faster droplets eject. Although it helps the droplets to speed up, reducing the nozzle size causes clogging up of the nozzles, so it is difficult to make use of that. On the other hand, from Equation (2), the oscillation period T_c is proportional to the square root of C_c, and as the C_c is strongly influenced by the dimension of the vibration plate, reducing the chamber compliance is very effective to shorten the oscillation period T_c.

In principle, the compliance of the vibration plate is proportional to the 5th power of the vibration plate width and is inversely proportional to the 3rd power of the plate thickness. Add to this, in the case of the MLChips type MACH, theoretically, the volume displacement of the vibration plate driven by the same voltage is proportional to the 3rd power of the width and is inversely proportional to the 2nd power of the thickness.

By optimizing both width and thickness of the vibration plate, i.e. reducing both width and thickness, for the specific droplet size, the consistent design with the evolution of the droplet size can be made.

Multi-Sized Droplet Technology

It is evident that small droplets size needs the large number of droplets to cover the whole media with ink. But the piezoelectric inkjet head is difficult to reduce the nozzle spacing and increase the number of nozzle in terms of cost. So if only the reduction of the droplet size is made, the print head would have to shuttle lots of times and this would result in a large drop in the throughput.

The MSDT (Multi-Sized Droplet Technology) can overcome this difficulty, ejecting differently sized ink droplets in one scanning. The number of scanning is defined by the largest droplet size the head can eject, not by the smallest.

Figure 10 shows the MSDT applied to MLP type MACH [5]. The pulse pattern from the common pulse generator, applied to each piezo transducer, has two driving pulses in one cycle, corresponding to the pixel grid point. When the switch of the piezo transducer selects the pulse part2, small droplet of 3pl would eject and form a small dot (Figure 10[C]). When the pulse part3 is selected, large droplet of 10pl would eject and form a middle dot (Figure 10[D]). In the case that both pulses are selected, the large droplet would be larger than the case D by the effect of the preceding small dot ejection, two droplets would eject and total ink volume of 19pl would form a large dot (Figure 10[E]).

In the MSDT, the drive waveform is designed so that the droplets with different sizes would have about the same velocity. While the simple Pull-Push operation would eject droplets twice as fast as the Push-Pull operation, by taking large Pull and small Push, the smaller droplet ejection was made possible.

Also in the MSDT, new idea of the Pull-Push-Pull operation, which is the combination of the Pull-Push and the Push-Pull, is implemented. The last Pull is set to cancel the previously generated flow like the Push-Pull operation. The response to this complex waveform can be easily understood by the superposition of the oscillations generated by each pulse edge.

Evolution of the Piezo Inkjet Technology

As above described, the piezoelectric inkjet head can precisely control the ink meniscus motion and change the droplet volume by means of the driving signal. This controllability made possible to adapt the inkjet heads to plenty of ink and media combinations and apply them to from the photo quality home print to the professional large format and arts.

From the viewpoint of the droplet size, if only a small droplet is pursued, it is easy to establish a new record. On the other hand, piezoelectric inkjet head can accept a variety of inks other than water base inks. These potentials can lead the piezo inkjet head to the new application area of the marking technology.

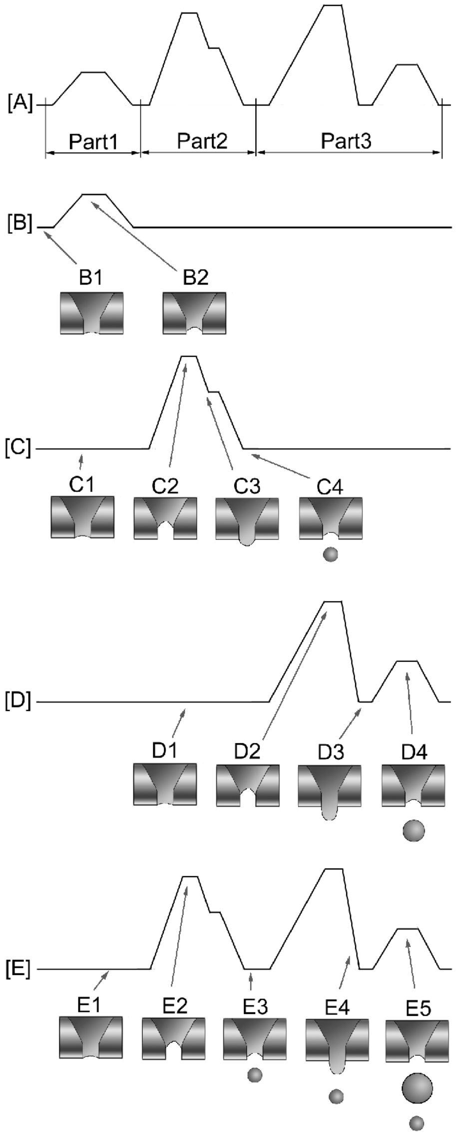

Figure 10. Driving waveform of MSDT

Conclusion

The piezoelectric inkjet heads has been evolving at marvelous speed, introducing new actuators. The high linearity of the actuators has given the high controllability, and the design flexibility and ultimate optimizing technique established applicability of the piezo inkjet technology to the all sort of digital printings.

References

1. M. Fujino, *Proc. SPIE*, Vol. 3963, pp. 340-348 (2000).
2. E. L. Kyser, S. B. Sears, *US patent 3,946,398*, (1976).
3. T. Kitahara, *Proc. IS&T's 11th International Congress on Advances in Non-Impact Printing Technologies*, pp. 346-349 (1995).
4. M. Usui, *Proc. IS&T's 12th International Conference on Digital Printing Technologies*, (1996).
5. T. Kitahara, *Japan Hardcopy '99*, pp. 335-338 (1999).

Biography

Shinri Sakai is a chief specialist in the Printer Development Division of SEIKO EPSON Corporation. He received his B.E. and M.E. in mechanical engineering from the Tokyo Institute of Technology, Japan, in 1983 and 1985 respectively. He worked on electrophotography system for three years and currently is working on ink jet printing system development. His primary responsibilities are mechanical and physical analysis and computer simulation for ink jet head development and optimization. His recent interests are rheological features of inks and their contribution to ink meniscus control and droplet formation.