Improvement of Drive Energy Efficiency in a Shear Mode Piezo Inkjet Head

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Summary

Recent improvements of inkjet printer technology enabling the high print quality and high-speed printing have been remarkable, however, for higher-speed printing, the development of multi-channel inkjet head whose energy efficiency is higher, is necessary. We have analyzed an ink flow in a shear mode piezo inkjet head and an ink droplet forming process through computational simulation. By using the results of the simulation, we designed optimum shapes of an actuator, an ink channel and a nozzle, and made a prototype of inkjet head employing a funnel type nozzle. Then we experimentally confirmed an improvement of the drive efficiency.

Abstract

The recent acceleration in high print quality and high-speed inkjet printers commands the development of an energy efficient multi-channel print head to accommodate these ever-advancing printers. In response, we have computationally simulated a shear mode inkjet head in order to analyze its fluid flow dynamics and jet forming process. As a result, we have been able to optimize the shape of the actuator, channel, and nozzle of the inkjet head. In particular, a funnel type nozzle has proven to provide good energy efficiency in a prototype print head based on the results of our simulation and analysis.

1 Introduction

For increasing the printing speed of the inkjet printer, the improvement of the ink-ejecting rate of the print head is a matter of course, and the number of channels needs to be increased.

For increasing the number of channels, the problem in the structure including the manufacturing is important, and it is also important to improve the drive efficiency to minimize energy necessary for droplet ejection, for controlling deterioration of print quality and droplet ejection stability caused by temperature rise of the print head during printing.

In order to overcome this problem, we analyzed the drive efficiency characteristics of a shear mode piezo inkjet head through computer simulation. The shear mode piezo inkjet head is a head driven by shearing stress generated by applying an electrical field in the direction perpendicular to the polarization direction of the piezoelectric material. The characteristic of an actuator composed of such piezoelectric material was analyzed by using a finite element method simulation software that can make a structure and an electrical field to be coupled, and for the ink flow within the print head and for the process of droplet ejection from the nozzle, a finite difference method simulation software which can analyze free surface flow, was used.

The electric energy applied to the actuator, the elastic energy applied to the ink in channels, and the kinetic energy of the droplet were estimated through the simulation, and the relationship between the factors (such as shapes of actuator and channel, nozzle shape, piezoelectric material, adhesive layer, ink characteristics, drive voltage waveform) and drive efficiency, was analyzed. Herein, the relationship between the shape of inkjet head and drive efficiency will be mainly discussed.

2 Structure of the inkjet head and driving energy

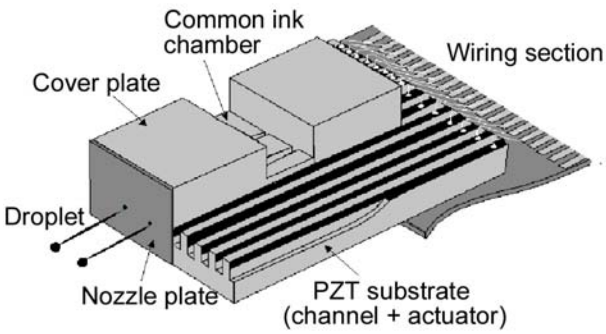

Fig. 1 Structure of shear mode piezo inkjet head

Fig. 1 is a structural view of a shear mode piezo inkjet head. When grooves are mechanically formed in a PZT (lead zirconate titanate) substrate, channels and actuators which are walls of channels are formed. A cover plate is bonded on the upper surface of the walls, and a nozzle plate is bonded on the front surface of the substrate, and the ink is fed into the channels.

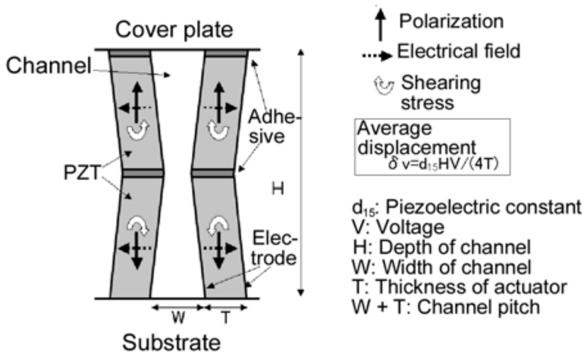

Fig. 2 PZT actuator (cross section)

A sectional view of the actuator that is cut at a right angle to the flow direction of channel is shown in Fig. 2. When an electrical field is applied in the direction orthogonal to the polarization direction of the PZT, actuators are deformed, and the ink in the channel is pressurized. When the pressure wave generated in the channel is reflected between nozzles and the common ink chamber, and resonated, the pressure applied to the nozzle change in time, and an ink droplet is ejected.

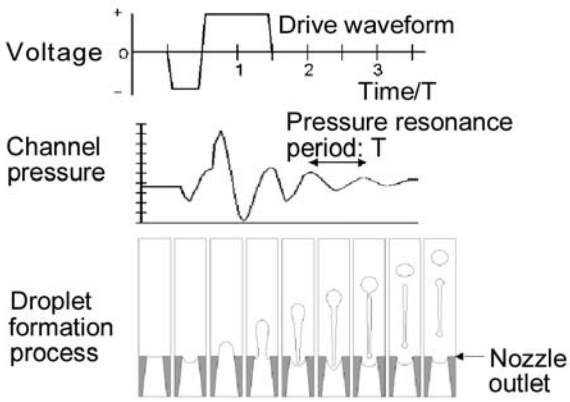

Fig. 3 Droplet ejection process

A result of the simulated droplet ejection process is shown in Fig. 3. For low voltage drive, the drive waveform shown on the upper part in Fig. 3 is used. When the voltage is changed, pressure generates within the channel, after that, it oscillates at a resonance frequency and gradually attenuates. (middle in Fig. 3). At the time of the rise of voltage applied in the direction in which the volume of channel is increased, negative pressure is generated. When the negative pressure reaches the peak of the positive pressure after a half period, the voltage is applied in the direction in which the channel volume is decreased, that is, in the reverse polarity to the first rise of the voltage. Then the positive pressure for droplet ejection is reinforced. The result of the simulation of the time change of the pressure in the channel and the process of forming droplet from the nozzle, is shown in the lower part of Fig. 3[(1)].

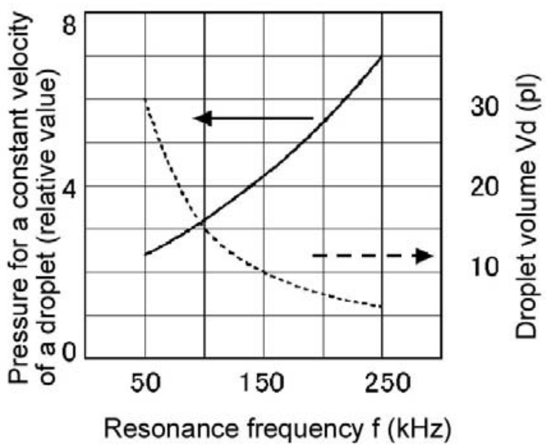

Fig. 4 Resonance frequency vs. droplet ejection

For the higher speed and higher print quality, it is necessary to enhance the pressure resonance frequency in the channel. The reason for this is that the droplet volume is inversely proportional to the resonance frequency, as shown by the following expression.

$$Vd = \pi r^2 \times v/(2 \times f)$$

Vd: Volume of droplet r: Radius of the nozzle
v: Velocity of droplet f: Resonance frequency

The computation result of the relationship between the resonance frequency of the pressure applied to the nozzle and values of the necessary pressure for constant velocity of a ejected droplet is shown in Fig. 4. When the frequency is increased, the necessary ejection pressure increases rapidly, that is, the drive voltage is increased.

Further, when the number of channels or the drive frequency is increased to improve printing speed and print quality, the generated heat (including the heat generated in the drive circuit) also increase rapidly.

$$Wa = (1/2) \times C \times V^2 \times A \times fd \times N$$

Wa: Total generated heat,
C: Electrostatic capacity of the actuator,
V: Drive voltage
fd: Drive frequency
A: Waveform coefficient
N: Number of channels

Some part of this generated heat, namely the heat generated by the dielectric loss of the piezoelectric material forming the actuator, and by the resistance of electrode transfer to the ink in the channel, and causes the ink temperature rise. Because of the short distance between the actuator and the ink, ink temperature rises in a very short time, and changes in ink characteristics cause fluctuations of the droplet velocity and droplet volume, resulting in a decline in print quality. Further, when the temperature rise is remarkable, there is a risk that stable ejection can not be achieved.

3 Shape of inkjet head and drive efficiency

3.1 Actuator and ink channel

A calculated example of the actuator displacement by voltage application is shown on the left side in Fig. 5. The compliance (displacement /force) of the actuator is calculated as a counter pressure displacement by the internal pressure rise on the right side in Fig. 5. The ratio of the compliance of an actuator to the compliance of the ink in the channel is called the compliance ratio (kcr). The compliance ratio shows the ratio of the volume change of the actuator by pressure difference between the channels to the volume change of pressurized ink in channel.

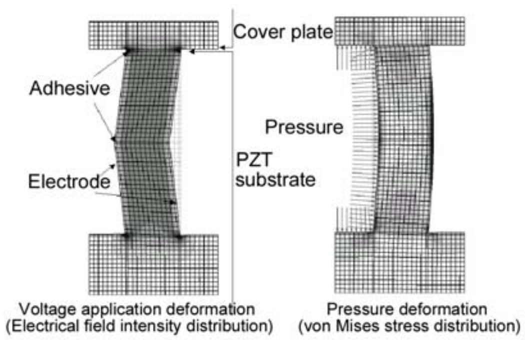

Fig. 5 Actuator deformation analysis

Pressure P generated in the channel by voltage application can be calculated using the following expression. Herein, λ is a constant determined by the channel drive pattern. The generated pressure is decreased because the actuator is forced back by the rise of internal pressure in the channel.

$$P = 2 \times (\Delta x/W) \times B \times V/(1 + \lambda \times kcr)$$

Δx: an averaged displacement of the actuator by unit voltage application
V: Drive voltage
W: Channel width
B: Bulk modulus of the ink

The speed of the pressure wave propagating in the channel is also changed depending on the value of the compliance ratio. The reason is that the change of volume of the ink by the channel internal pressure is practically increased by the deformation of the actuator, that is, bulk modulus of the ink is apparently decreased. Therefore, the change of shape also influences on the resonance frequency, then the attention must be paid.

Propagation speed of pressure wave

$$C_0 = (B/\rho)^{1/2}/(1 + \lambda \times kcr)^{1/2}$$

ρ: Density of ink

Resonance frequency of pressure wave

$$f = C_0(1 + \alpha)/4L$$

α: Shape factor
L: Channel length

Since the generated pressure is proportional to the displacement of the actuator, it is essential to design so that the displacement per unit of applied voltage is increased. The relationship between the displacement and the elastic energy applied to the ink is determined by the following expression.

$$E = (1/2) \times B \times (x/W)^2 \times L \times H \times W$$

E: Elastic energy of to the ink
x: Average displacement of the actuator
L: Channel length

W: Channel width
H: Channel depth

Further, the relationship between pressure P generated in channel and the energy is expressed by the following expression:

$$E = (1/2) \times P^2 \times L \times H \times W/B$$

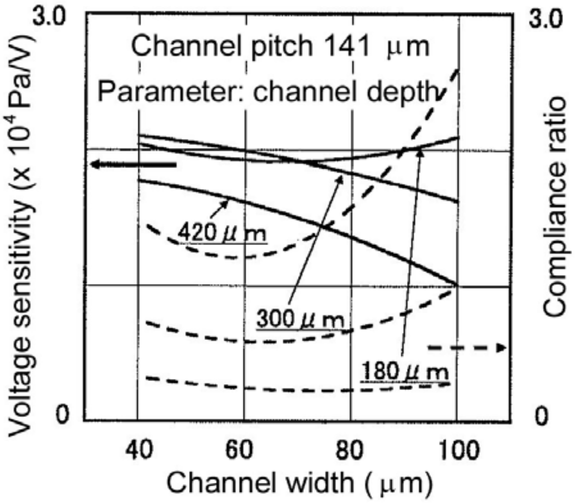

Fig. 6 Voltage sensitivity vs. channel width

Fig. 6 shows an example to calculate how the ratio of voltage sensitivity and compliance ratio are changed when the channel width is changed under the constant channel pitch (channel width + actuator thickness). When the channel is shallow, even when the channel width increases, the compliance ratio (dashed line) is only slightly increased, then the voltage sensitivity (solid line) does not drop. When the channel depth is increased, the compliance ratio increases rapidly, then the voltage sensitivity drops sharply as the channel width increases. Fig. 7 shows the relationship between channel width and elastic energy in which the channel depth is a parameter. When channel depth is decreased, even when voltage sensitivity is high, the elastic energy is lowered because the section area of the channel is decreased.

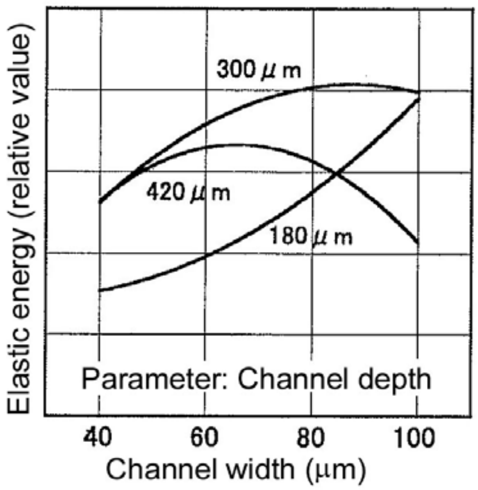

Fig. 7 Ink elastic energy vs. channel width

It is important to design the shapes of the actuator and channel so that efficiency of conversion from input electrical energy to ink elastic energy increases. However, it must be realized that the electrostatic capacity of the actuator changes depending on its shape. The electrostatic capacity is proportional to the channel length and to its depth, and is inversely proportional to the thickness of the actuator. Further, the optimum cross sectional shape changes depending on the characteristic of the piezoelectric material (piezoelectric constant, relative dielectric constant, elastic constant), the characteristic of the ink (bulk modulus) or an adhesive layer [1]. The resonance frequency of the channel is also influenced by the cross sectional shape, however, it is almost inversely proportional to channel length. Fig. 8 shows how the resonance frequency is changed for the channel length.

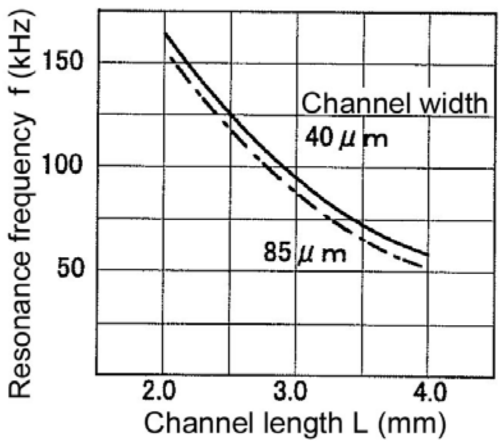

Fig. 8 Channel length vs. resonance frequency

3.2 Nozzle

When a nozzle diameter is decreased, the droplet volume decreases, however, the viscous resistance in the nozzle is greatly increased, and the energy loss grows greater. The Fig. 9 shows the relationship between the nozzle diameter and the droplet velocity, in which the ink viscosity is a parameter. In the case where ink viscosity is high, if the nozzle diameter is decreased, a lowering of ink velocity is remarkable. The reason is that velocity down effect of the viscosity is greater than the velocity up effect of the accelerated flow rate by the ratio of cross sectional area of the channel to that of the nozzle.

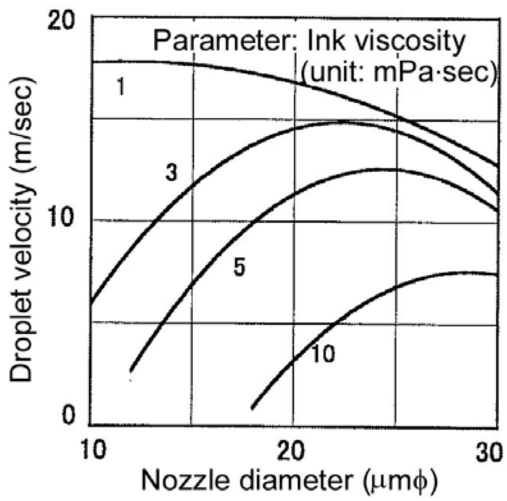

Fig. 9 Nozzle diameter vs. droplet velocity

Particularly, in the case of high viscosity ink, when resistance of the nozzle is decreased, the increase of ink droplet velocity is large. Fig. 10 shows a change of droplet velocity, in the case of changing the taper angle of nozzle.

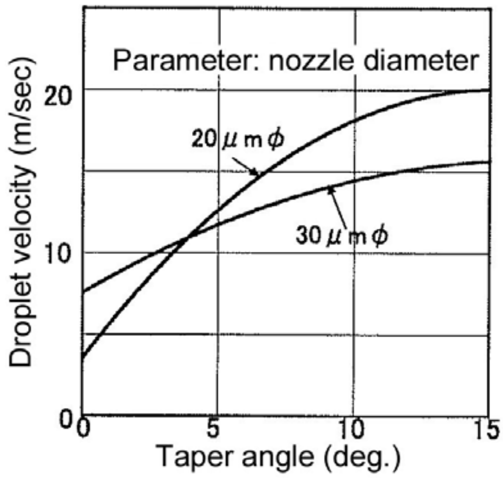

Fig. 10 Taper angle vs. droplet velocity

When a nozzle diameter is small, the influence of taper angle is great. In order to reduce nozzle resistance, it is also effective that the length of nozzle is reduced, whereby however, the stiffness of the nozzle plate is also reduced, and the pressure in the channel is lowered by the increase of compliance, and the fluctuation of the jet trajectory increases.

Further, the taper angle can not also be increased, because it affects a jet trajectory accuracy. In addition, viscous resistance of the nozzle largely influences on the ink replenishment time after droplet ejection as well as on attenuation of the pressure wave, and therefore, attention must be paid to the design of nozzles [1].

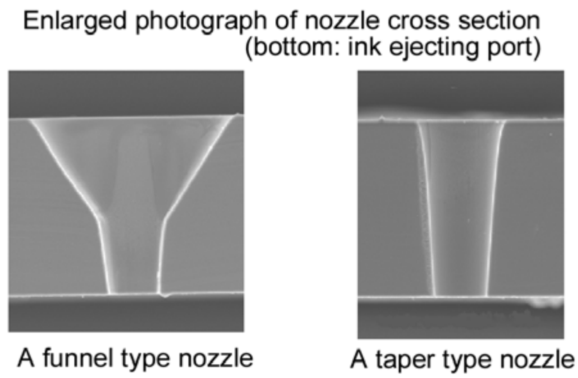

Fig. 11 SEM photograph of nozzle cross section

In order to reduce energy loss and to stabilize the jet trajectory, a funnel type nozzle shown on the left side in Fig. 11 shows good characteristics. Fig. 12 is an example in which the droplet velocity was calculated when the nozzle diameter was changed on a taper type nozzle and a funnel type nozzle. Compared to the conventional taper type nozzle having a small taper angle, a greater increase of droplet velocity can be expected.

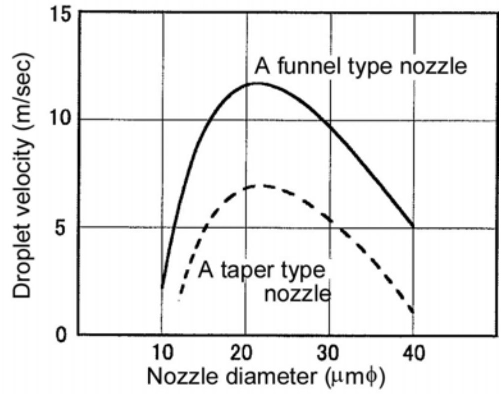

Fig. 12 Nozzle shape vs. droplet velocity

4 Characteristics of the prototype print head

In accordance with the result of the simulation, the shapes of the actuator and the channel were designed to achieve high drive efficiency, and a print head whose nozzle shape was changed from the conventional taper type to the funnel type was made on a trial basis. Specifications of the prototype print head are shown in Table 1. As drive method of the print head, a so-called 3-cycle firing by which the ink is ejected every three channels at a time and the drive of all channels is completed by 3 cycles was used, because of the actuators that are shared for the adjoining channels. Further, an oil-based ink with a relatively high viscosity was used. The driving energy necessary for ejection of one droplet in this print head was 0.45 μJ.

Table 1 Specifications of prototype head

Nozzle	Funnel Type	Ink
droplet volume	15 pl	Viscosity 10 mPa·sec
drive frequency	13 kHz	surface tension 28 mN/m
number of channels	512 ch.	density 0.89 g/cm^3
channel array density	180 dpi	

5 Consideration

Driving energy for the shear mode piezo inkjet head is imparted to the actuator as electrical energy, and the greater part of the energy is consumed in the drive circuit, and a part of the rest is converted to elastic energy in the ink in the channels by a displacement of the actuator. This elastic energy propagates in the channel as a pressure wave to form a standing wave. Then, it pressurizes the ink in the nozzle to eject a droplet.

The required energy to eject the ink droplet includes the energy to form the droplet surface and the kinetic energy of the droplet, and in addition, a considerable energy is consumed for the flow of the ink in the nozzle. Further, even after droplet ejection, more energy is consumed until the residual oscillation of the ink is terminated.

When the driving energy of the prototype inkjet head is roughly calculated, the elastic energy of the ink in each channel is 6 nJ, which is nearly two-digit smaller than the electrical input energy of 0.45 μJ, and the droplet surface forming energy is 0.08 nJ, and the droplet kinetic energy is about 0.22 nJ.

The shapes of the actuator, channel, and nozzle were optimized based on the computational simulation analyses, the results were that a prototype print head proved that its drive efficiency was twice or more than the conventional one.

6 Conclusion

On the basis of driving efficiency analyses of the shear mode piezo inkjet head through computational simulation, the channel shape or nozzle shape have been optimized, and an inkjet head of better drive efficiency was made on a trial basis. If the electrostatic capacity of wiring section is reduced, the efficiency can further be raised several times.

Since the fabrication of the shear mode piezo inkjet head of a multi-channel type is comparatively easy and a high efficiency drive is possible [(3)], the shear mode piezo inkjet head is promising as a head for a higher speed and a higher print quality printers in near future.

• References

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