Development of New Inkjet Head Applying MEMS Technology and Thin Film Actuator.

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Abstract

We developed a new inkjet head by applying MEMS technology and thin film piezo actuator. Jetting properties of inkjet heads were calculated by the simulation method of the equivalent circuit model generated from actuator properties and ink flow channels of the inkjet head.

We manufactured a test piece to investigate the jetting properties and oscillation forms of the actuator. As a result, our test piece was driven at maximum 70 kHz and ejected 3 pl droplet with an ink which viscosity was 10 mPa · s. We found that the experimented jetting properties and vibration forms agreed very well with the simulation.

1. Introduction

Konica Minolta, Inc. introduced newly developed inkjet printer "KM-1" at drupa 2012. Figure 1 shows an image of KM-1. This printer can print on up to B2 paper size with 1200 x 1200 dpi resolution at the speed of maximum 3300 sheets per hour simplex [1]. Recently, demands for high-speed and high-resolution printers are increasing more and more; this machine is one of the answer for these demands.

***Figure 1**. KONICAMINOLTA KM-1*

Developing a small-sized, high-speed and high nozzle density inkjet head is demanded for achieving the high printing performance. Reducing the printing head cost is also needed because the number of print heads for one printer will increase more in the future. To meet these requirements for inkjet heads, we are trying to develop a new inkjet head by applying MEMS technology and thin film actuator. Inkjet head using thin film actuator is becoming popular recently [2]. We can arrange high density nozzles into the inkjet head with lower cost by using thin film actuator because they are manufactured by patterning a thin piezo film coated on a Si substrate.

We had reported the development of inkjet head utilizing MEMS technology for printed electronics applications at NIP 28 [3]. That head consisted of silicon (Si) actuator plate attached a piezo ceramic element (bulk actuator) and Si nozzle plate.

By modifying that, we designed a new inkjet channel which satisfied the jetting property as planned. We changed the design of pressure chamber in the Si actuator plate and replaced a "thick" piezoelectric ceramic element with a "thin" film piezo element. We used equivalent circuit model simulation to estimate the properties of our channel. This method can calculate several jetting properties including jetting frequency, driving voltage, droplet size and droplet speed.

In this paper, we show the specified structure of our test piece and simulation method. We also show the results of the calculated properties and experimented jetting properties of our test piece.

2. Structure of the test piece

Figure 2 is a cross-sectional view of an individual channel of the designed test piece.

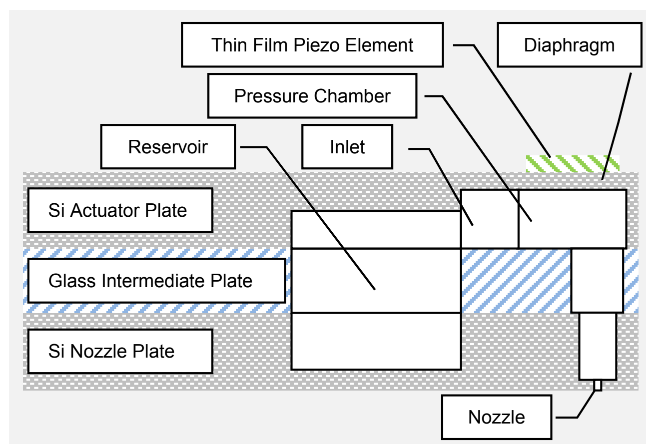

***Figure 2**. Cross section of an individual channel of the thin film MEMS head*

The MEMS head chip having a total thickness of approximately 500μm consisted of three plates; a nozzle plate, an intermediate plate, and an actuator plate. The nozzle plate and the actuator plate were constructed by using Silicon on Insulator (SOI) substrate which had been polished by means of chemical mechanical polishing (CMP) to provide a designed thickness. On actuator plate, lower electrode layer, thin piezo film layer and upper electrode layer were deposited on the SOI substrate by this order. After that, electrode layers and thin piezo film layer were patterned by dry or wet etching process and then it came to thin film piezo element. Next, Si actuator plate and nozzle plate were accurately processed by the deep reactive ion etching (DRIE) process. The intermediate plate was created from a glass substrate which had been processed by a blast processing method. Finally, those three plates were accurately bonded together; thus, the MEMS head chip has been configured.

Figure 3 shows a SEM image of the thin film actuator. Imposed figure in Fig.3 is a cross sectional image of a thin piezo film. Piezo film consisted of highly oriented crystal and showed excellent piezoelectric coefficient.

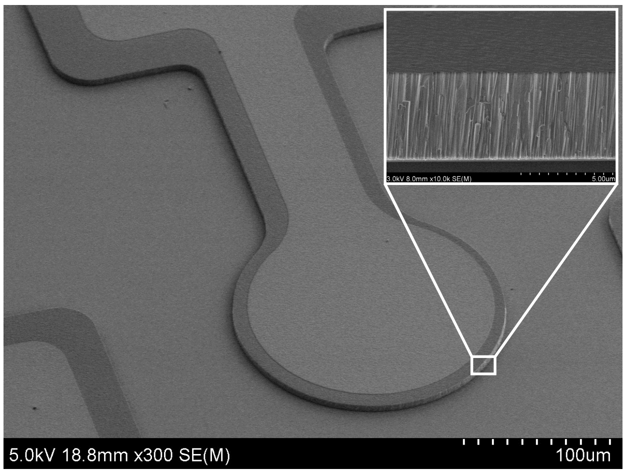

***Figure 3**. SEM image of thin film actuator and cross section of thin piezo film*

Design of ink supply and main frame was almost the same as the former reported MEMS head with bulk actuator. The top cover plate was modified to a glass plate to observe the oscillation of actuator. Figure 4 shows the outside appearance of the test piece. The glass cover plate transmits laser beams and enables us to watch the oscillation by using a laser Doppler vibrometer. Usually, precise observation of the actuator displacement is difficult because it is too small to detect. The thin film actuator has a thin membrane and it vibrates about one micrometer when a droplet is ejected. Then, we can evaluate the displacement accurately.

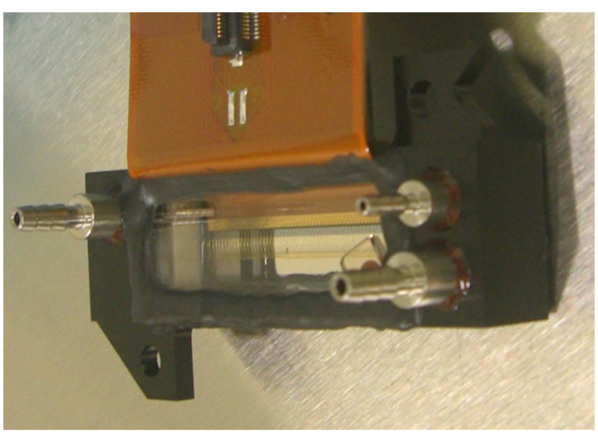

***Figure 4**. The outside appearance of the test piece*

3. The simulation method

Piezoelectric inkjet print head is generally divided into two parts; actuator and ink flow channel. Coupled analysis is needed because these two parts are connected with each other when the inkjet head ejects a droplet. For that reason, equivalent circuit model was applied by replacing oscillation of an actuator and fluid with electronic circuit [4].

Movement of an electrical charge is described by following equation (1). On the other hand, mechanical oscillation of the actuator is described by following equation (2) and acoustic oscillation of the fluid is described by following equation (3) respectively.

$$L\frac{d^2Q}{dt^2} + r_e\frac{dQ}{dt} + \frac{1}{C_e}Q = V \quad (1)$$

$$m\frac{d^2x}{dt^2} + r_M\frac{dx}{dt} + \frac{1}{C_M}x = F \quad (2)$$

$$M\frac{d^2X}{dt^2} + r_A\frac{dX}{dt} + \frac{1}{C_A}X = P \quad (3)$$

Each model can be replaced equivalently because all of these three equations are secondary differential equations about time and have the same equation form. Table 1 shows correspondence in each field.

Table 1. Correspondence in each field

(1) ELECTRIC	(2) MECHANICAL	(3) ACOUSTIC
V : voltage	F : force	P : pressure
Q : electric charge	x : displacement	X : volume flow
I : electric current	u : velocity	U : volume flow-rate
r_e : resistance	r_M : resistance	r_A : resistance
C_e : capacitance	C_M : compliance	C_e : capacitance
L : inductance	m : mass	M : inertance
Z_e : impedance	Z_M : impedance	Z_A : impedance

The basic simulation model as shown in figure 5 was formed by using this method. In this model, ink chamber part was divided into three portions to consider pressure distribution of the chamber. The jetting properties and actuator oscillation of designed test piece were calculated by this model.

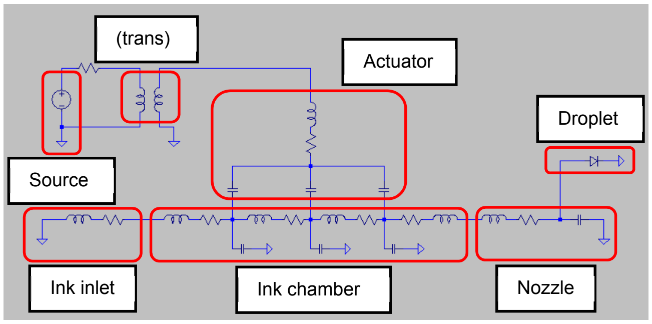

***Figure 5**. Equivalent circuit model (basic model)*

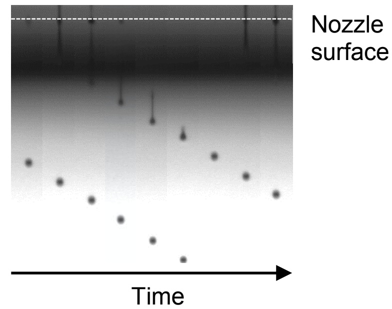

***Figure 7**. Sequential stroboscopic image of droplet*

4. Result and discussion

A test piece with thin film actuator was fabricated by using MEMS process. Figure 6 shows design drawing and manufactured channel. The dimension of the test piece pattern corresponded with the design well. Jetting properties and diaphragm oscillation were evaluated with this test piece.

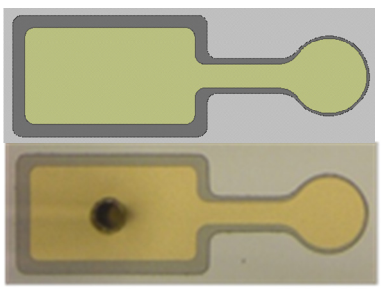

***Figure 6**. A test piece pattern design (top) and a test piece (bottom)*

4.1 Jetting properties

Jetting properties were evaluated with a solvent ink which viscosity was 10 mPa·s. Ejected droplets were measured by a drop watcher. Table 2 shows comparison between calculated and measured properties. Measured ejecting properties of the test piece agreed very well with the simulated properties. That means our simulation method can predict the head performance appropriately.

Table 2. Comparison between calculated and measured properties

Properties	Simulation	Measurement
Jetting frequency	71 kHz	70 kHz
Drive voltage	29 V @7 m/s	28 V @7 m/s
Sensitivity	0.4 m/s/V	0.5 m/s/V
Droplet size	3.0 pl	3.1 pl

Figure 7 shows a sequential stroboscopic image showing the ink drop ejecting condition with the rectangular wave at 15 kHz.

The drawing verifies that droplets have been ejected without creating satellites. (Drop Velocity is 6m/sec)

4.2 Actuator oscillation

Actuator oscillation was measured by using a laser Doppler vibrometer and calculated by the simulation. Figure 8 shows the schematic image of actuator oscillation observation system.

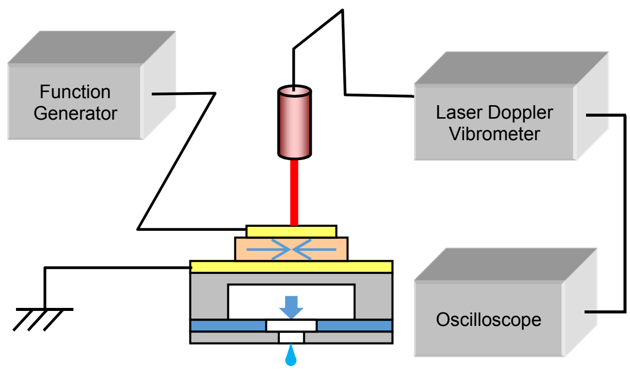

***Figure 8**. Schematic image of actuator oscillation observation system*

Figure 9 shows the calculated oscillation and measured one respectively. Both results corresponded well and reverberation vibrations are seen in the graph.

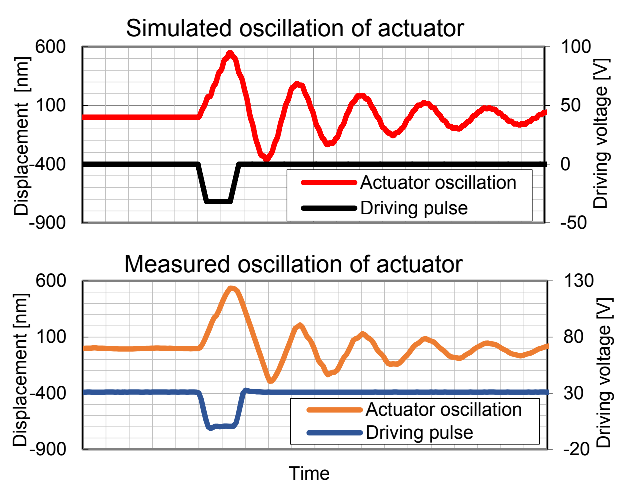

***Figure 9**. Calculated diaphragm oscillation (top) and measured one (bottom)*

Reverberation vibrations disturb the actuator's oscillation for the next droplet when jetting frequency become fast. Therefore, they should be eliminated by introducing a cancel pulse in driving wave form.

Figure 10 shows actuator oscillation when driving wave form with a cancel pulse was applied. The cancel pulse was optimized to eliminate the reverberation vibrations with a laser Doppler vibrometer observation. By using this wave form, drop velocity dependence on jetting frequency was improved as shown in figure 11. As a result, we confirmed the effectiveness of the counter pulse to reduce the drop velocity change; the velocity change was suppressed even in the higher frequency region over 40 kHz.

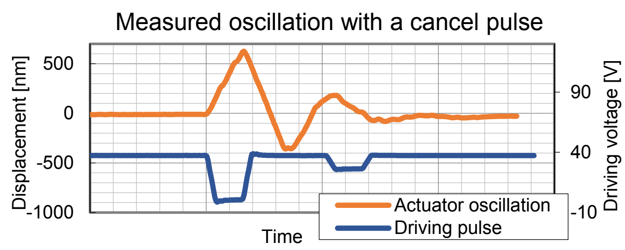

***Figure 10**. Measured oscillation with cancel pulse*

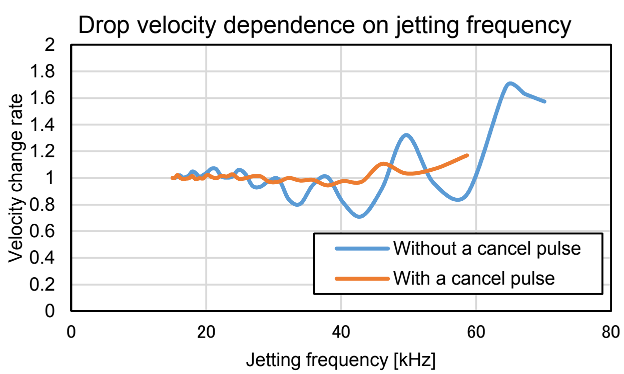

***Figure 11**. Drop velocity dependence on jetting frequency*

Actuator oscillation also gave information of chamber condition. When an air bubble exists in the chamber, the oscillation frequency increases because the total ink volume in the chamber decreases. Figure 12 shows the oscillation with an air bubble. Though the driving wave form was the same as the case of figure 10, the measured oscillation in figure 12 had a different shape. This was because the oscillation frequency increased due to the air bubble and the timing of the counter pulse changed.

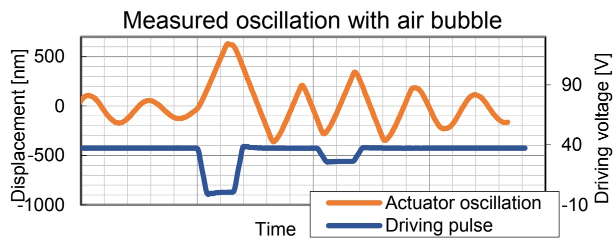

***Figure 12**. Measured oscillation disturbed by an air bubble*

If the volume of the air bubble in chamber increases, the air bubble works as a dumper and attenuates the actuator's force and the channel becomes ink discharge failure. By monitoring actuator oscillation, an air bubble in a chamber can be determined.

5. Conclusion

We developed a new MEMS head with thin film actuator by modifying the MEMS head with bulk actuator. We used equivalent circuit model to design channel dimension of the head and we confirmed the jetting properties by manufacturing a test piece. The calculated and measured properties coincided well and we verified that the simulation method was applicable to the thin film actuator. The test piece showed the thin film actuator was able to be driven at maximum 70 kHz and to eject 3 pl droplet with a solvent ink which viscosity was 10 mPa·s.

We succeeded to observe the actuator oscillation directly by using a laser Doppler vibrometer. The observed vibration wave form also agreed with the simulated one. Observation of the oscillation could optimize the driving wave form easily and detect the defect due to an air bubble inside of the chamber.

In the future, we will develop a novel MEMS head with high nozzle density by applying thin film actuators to satisfy the requirement of high-speed and high-resolution inkjet printers.

References

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Author Biography

Kenji Mawatari received his B. S. and M. S. degree in physics from Tohoku University in 2006 and 2008. Since then he has worked in the Research and Development Division at Konica Minolta Inc. He has focused on MEMS inkjet head development.