DEVELOPMENT OF INKJET NOZZLE DRIVEN BY DOUBLE PIEZO ACTUATORS

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ABSTRACT: *An inkjet nozzle with double piezo transducers has been designed, which is different from conventional inkjet nozzles. The body of the nozzle which is fabricated by precision machining techniques is made from transparent acrylic material to visualize the flow inside the nozzle. The piezoelectric actuators are activated by a voltage amplifier which generates high-voltage bipolar waveforms. The key idea of the present nozzle is a successive actuation of multiple piezoelectric actuators, which makes the ejection and suction of liquid more controllable than the single piezoelectric actuator. The present study presented the effect of the pulse widths and the time delay between the double piezo transducers on the formation and speed of droplet during the ejection.*

1. Introduction

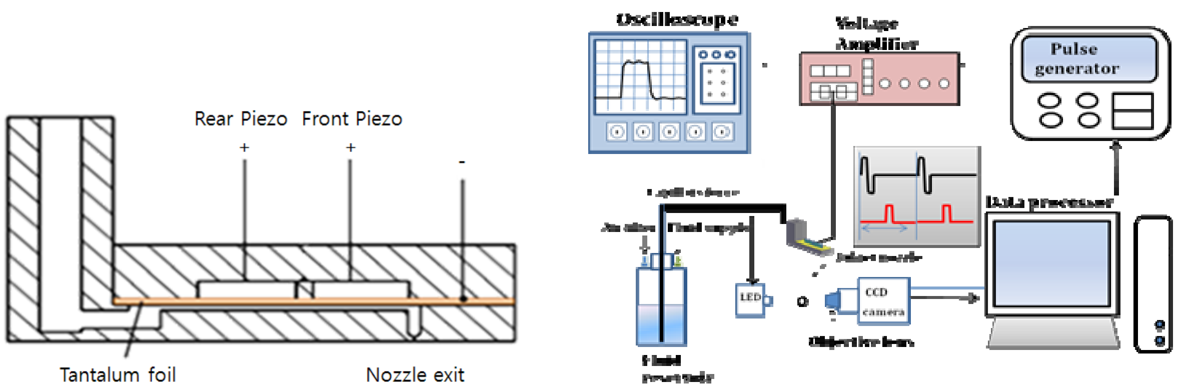
Printing of conductive materials for the fabrication of electronic components and devices becomes now an attractive technology in the electronics packaging. It can reduce a total number of processes through the direct writing technology (DWT) using drop-on-demand (DOD) inkjet nozzles [1]. In the previous fabrication of electronic devices, the successive procedure of deposition, lithography and etching is required to make patterns on a wafer. On the other hand, in the direct writing approach, patterns or structures can be obtained directly without the use of masks photography and chemicals for etching, and thus it is low cost, high-speed, non-contact and environmentally friendly [2].

One of the key points to control droplets by piezo inkjet actuator is to predict pressure behavior inside the channel and manipulate it by adopting suitable waveforms. In most previous researches, a single square waveform has been applied to single piezo actuator [3-5]. To improve performance of droplet formation through an inkjet nozzle, new waveforms have been proposed by various groups. Chen and Basaran [6] applied a waveform which consists of a succession of three square pulses. In their waveform, satellite was suppressed by the operation of the second negative voltage. Dong et al. [7] has analyzed experimentally ejection, stretching and pinch-off of liquid thread from the nozzle using a double peak waveform. Sakai [8] reported that the waveform with two driving pulses in one cycle can control the meniscus motion and change the droplet volume.

However, above researches have structural limitation to control the pressure inside the channel, because they only used single piezo transducer attached to a circular channel. The present study concerns about double piezo transducers attached to a rectangular channel. An inkjet nozzle with double piezoelectric transducers can dispense various kinds of ink, from low to high viscosity liquids as well as conductive ink, bio materials and so on, since it has more control parameters than the single piezo transducer. The cross section of the channel is rectangular, which makes mass production possible by taking the advantages of MEMS or precision machining techniques. Regarding inkjet nozzle with a rectangular channel, Meinhart & Zhang [9] measured velocity fields inside an inkjet nozzle using a PIV technique, and Lee & Kim [10] monitored remaining pressure inside a channel by making use of a piezo actuator as a pressure sensor.

The purpose of the present study is to develop an inkjet nozzle driven by double piezo actuators attached to a rectangular channel. The inkjet nozzle is fabricated by precision machining technique. To drive each piezo actuator, a bipolar waveform with high voltage and high slew rate is applied with a time sequence. The main control parameters are the pulse width and the time delay between the double piezo transducers. After measuring the optimum pulse width for each piezo transducer, the effects of control parameters on the formation and speed of droplet are investigated when they deviate from the optimum pulse.

2. Experimental setup



(a) (b)

Fig. 1 Schematics of (a) the piezoelectric inkjet nozzle and (b) the experimental set up for testing the droplet ejection.

The piezoelectric inkjet device which is designed for this study is shown in Fig. 1(a). Unlike conventional piezoelectric inkjet nozzle, double (front and rear) piezo actuators are applied for a single nozzle. The nozzle, 50 μm in diameter, is at the one end of the main channel whose dimension is 14 x 1.5 x 0.3 mm^3. The other end of the channel is connected to the water reservoir through a tube. As the membrane, the top of the channel is covered with a tantalum foil so that the pressure induced by piezo transducers is transmitted well to the fluid inside channel. The anodes are directly attached to the top of each piezo transducer (5 x 0.5 x 1.5 mm^3) and the cathodes are connected to the bottom of the piezo transducer through the foil. The body and upper housing fabricated by precision machining techniques are made from transparent acrylic material to visualize the flow inside the nozzle in further research. D.I. Water is used as a working fluid and the experiments are conducted at the room temperature (25°C).

The schematic of experimental set up is depicted in Fig. 1(b). Four square TTL signals from two pulse generators (Agilent, 33522A) are turned into two bi-polar waveforms by a simple electric circuit. The signal is amplified by a voltage Amplifier (Piezo system inc., EPA-104) and monitored by oscilloscope. To visualize the drop formation, a CCD camera (Teli, MD-O-538-85) with a microscope objective lens, an LED strobe and a video monitor are used. The LED strobe takes signal from the pulse generator, which makes it possible to control delay time of the strobe signal. The images of drop formation are recorded by the CCD camera at the arbitrary delay time from the rising edge of the driving pulse.

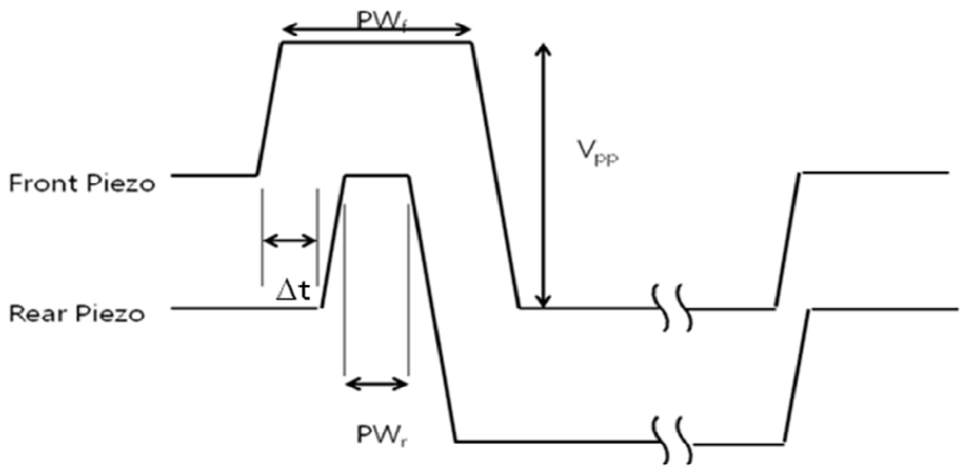


Fig. 2 The combination of driving waveform and the experimental parameters applied to the front and rear piezo transducers.

Fig. 2 shows the two waveforms of the driving pulses to control the double piezo transducers. One waveform is applied to the front piezo and the other to the rear piezo with a time delay and a different pulse width. When a rising (falling) edge of waveform is applied to a piezo transducer, the piezoelectric material on the channel expands (contracts) so that negative (positive) pressure wave is produced inside the channel. In the present study, a form of bipolar waveform as shown in Fig. 2 is used to produce a strong contraction force, where the widths of the positive pulses for the front (PW_f) and rear (PW_r) piezo actuators are the experimental parameters. In addition, the effect of the time difference (Δt) between both the positive pulses are considered. The widths of the negative pulses are fixed long enough so that the negative pressure induced by the last expand motion does not affect jetting procedure. The frequency of the waveforms is fixed to 50 Hz for all cases. This low operating frequency ensures enough time to damp out the traversing pressure waves inside the nozzle and thus eliminates the interference between the successive actuations.

By adopting double piezo transducers, a huge number of combinations of waveforms for each piezo transducer are possible to control the pressure inside the channel. The key idea of the present study is the sequential operation of the piezo pulses as shown in Fig. 2. When the rising edge of waveform is applied to the front piezo transducer, negative pressure wave is produced inside the channel. And then, the negative pressure wave travels both upstream and downstream of the channel. At the instance that the pressure wave travelling upstream arrives at the rear piezo transducer, if the rising edge of waveform is applied to the rear piezo transducer, the negative pressure is amplified. After the amplified pressure is reflected from the reservoir, its phase is changed from negative to positive and it continues to travel downstream. The application of falling edge in the pulse of the rear piezo transducer as soon as the positive pressure wave arrives at the rear piezo transducer, amplifies the positive pressure primarily. The successive application of falling edge in the pulse of the front piezo transducer makes it more amplified enough to eject the liquid out of the nozzle.

3. Results and discussion

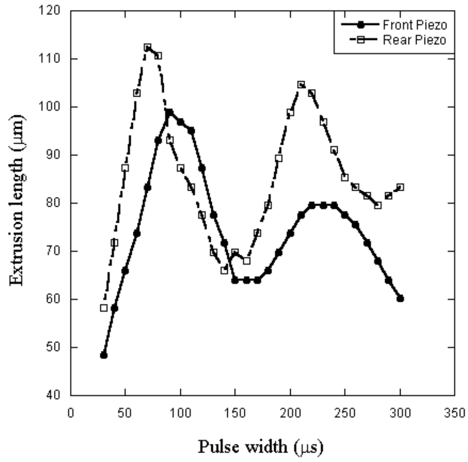


Fig 3. The meniscus extrusions according to the pulse widths of the front and rear piezo transducers.

Prior to investigating the characteristic of droplet formation by the double piezo transducers, the optimum pulse width for each piezo transducer needs to be measured. The optimum pulse width is defined by the pulse width at the condition that the maximum meniscus extrusion occurs in the status of no droplet ejection. Thus, the meniscus extrusion length is plotted in Fig. 3 for various pulse widths by activating only one of the two piezo transducers. For the front and rear piezo transducers, the optimum pulse widths are found to be 90 and 70 μs, respectively. The optimum pulse width for the front piezo is larger than that for the rear piezo transducers since the front piezo transducers is located further downstream from the reservoir than the rear piezo transducers. Note that the pulse width becomes optimum when the falling edge of the driving signal is synchronized with the instance that the travelling pressure wave reflected from the reservoir arrives just beneath the piezo transducer. If the pulse width is twice times than the optimum pulse width, the extrusion of meniscus becomes the smallest. In this study, the voltage amplitude of the front piezo pulse is set to be lower (V_{pp} = 360 V) than that of the rear piezo pulse (V_{pp} = 420 V) in order to prevent the working fluid from being fired. Thus, the overall extrusion length by the front piezo pulse is shorter than that by the rear piezo pulse. For the same voltage amplitude applied to each piezo transducer, the pressure at the nozzle induced by the front piezo transducer would be stronger than that by the rear piezo transducer due to the closer position of the front piezo to the nozzle.

In Fig. 4, the sequential images of the drop formation are compared for the different pulse width of the rear piezo transducer (PW_r). Here, the pulse width of the front piezo transducer is set to be its optimum pulse width (PW_f = 90 μs) and the voltage amplitudes are the same (V_{pp} = 420 V). The top figure is the result of PW_r = 80 μs and the bottom figure is the result of PW_r = 40 μs. Both the driving pulses are center-aligned so that the time delays of the rear piezo pulse with respect to the front piezo pulse are 5 and 25 μs, respectively. The time for each image of the droplet in Fig. 4 is relative to the rising edge of the front piezo pulse. When PW_r is 80 μs, there found a longer liquid thread during the ejection than the case of of PW_r = 40 μs. It means that higher pressure force acts at the nozzle when the pulse width of the rear piezo transducer gets longer. The long liquid thread observed at PW_r = 80 μs results in satellites due to the capillary wave formed on the free surface during the contraction of the liquid thread. On the other hand, at PW_r = 40 μs, no satellite occurs producing stable single droplet.

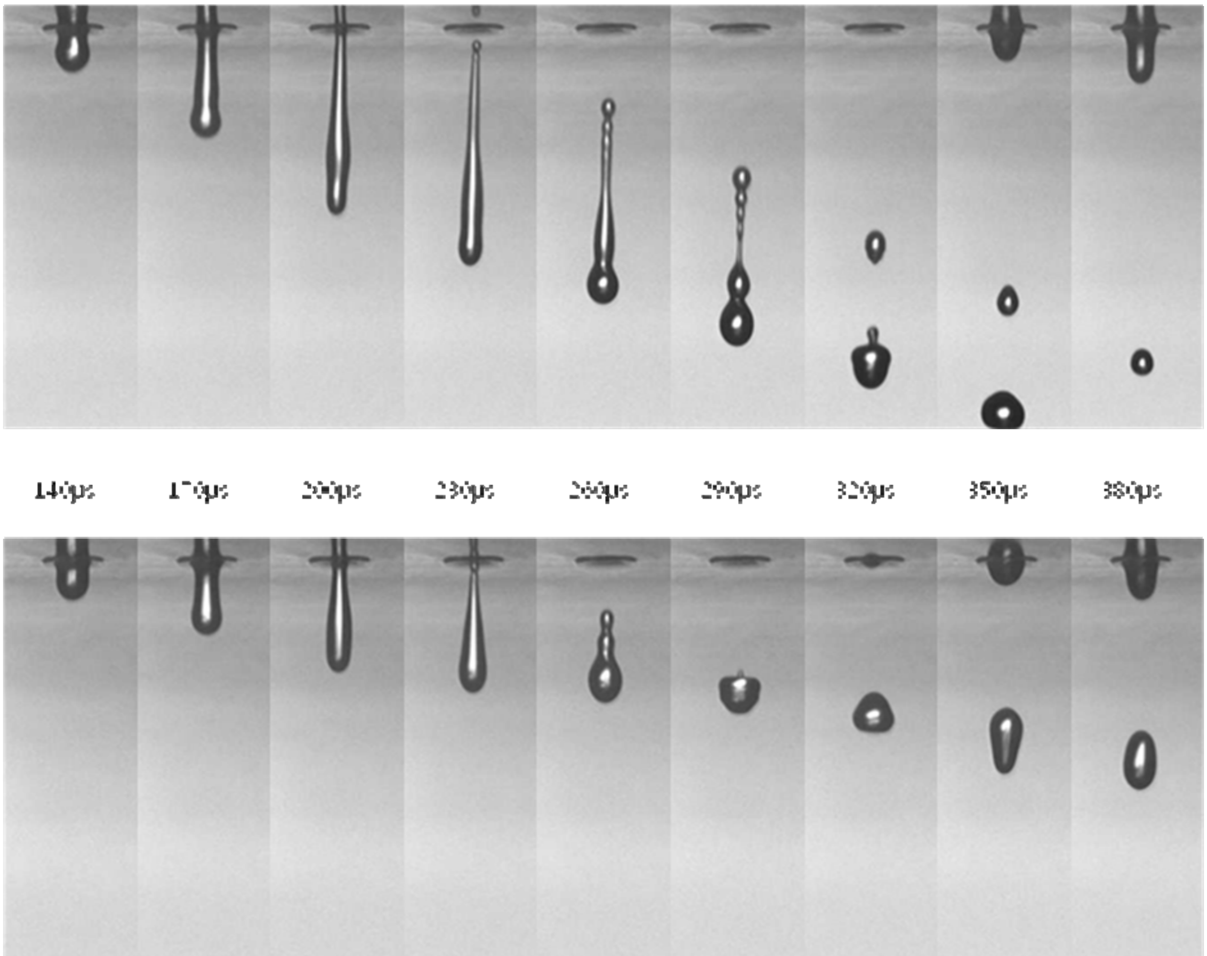
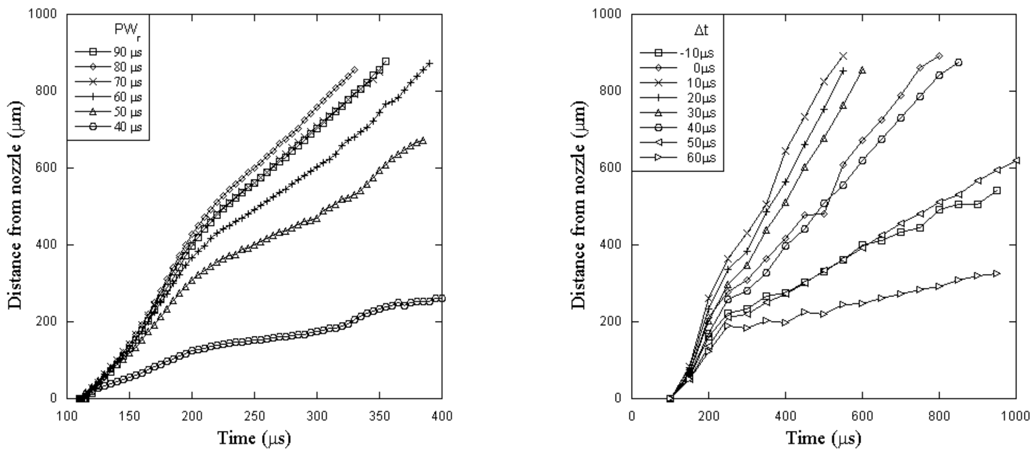


Fig. 4. Sequential images of droplet formation for the different pulse width of the rear piezo transducer; PW_r = 80 μs (top) and 40 μs (bottom).

Fig. 5 shows the trajectory of droplet head after ejected from the nozzle. In Fig. 5(a), the droplet positions for time are measured according to the change of the pulse width for the rear piezo transducer. It varies from 40 μs to 90 μs with being center-aligned with the pulse for the front piezo transducer. The pulse width of the front piezo transducer is fixed to its optimum pulse width 90 μs. In this figure, the increasing rate of the distance denotes the speed of droplet head. At the beginning of ejection, the speed of droplet head is nearly the same irrespective of PW_r. However, it decreases after the liquid thread is fully detached from the nozzle due to the surface tension force which makes the liquid thread contract. The decrease of the head speed is conspicuous as PW_r deviates from its optimum pulse width. In this experiment, the droplet speed is the fastest at PW_r = 80 µs and the slowest at PW_r = 40 µs. The reason why the maximum droplet speed does not happen at the optimum pulse width 70 µs seems that there is some interference between the two piezo transducers which are attached to one membrane. In Fig. 5(b), both PW_f and PW_r are fixed to their optimum pulse widths and the relative actuating time Δt of the rear piezo transducer to the front piezo transducer is shifted from -10 to 60 µs. In this figure, the speed of droplet is the fastest when Δt = 10 µs which is the same condition that the pulse of rear piezo transducer is center-aligned with the pulse of front piezo transducer. If the waveforms of the front and rear piezo transducers deviate from this condition, the droplet speed decreases with Δt. Thus, the most efficient driving waveform in the inkjet nozzle driven by double piezo actuators is the center-aligned condition with the optimum pulse widths.



(a) (b)

Fig. 5 Trajectory of droplet head after ejected from the nozzle; (a) PW_r varies with being center-aligned with the pulse of the front piezo transducer and (b) the relative actuating time Δt of the rear to front piezo transducer varies with PW_f and PW_r fixed to their optimum pulse widths.

4. Conclusions

An inkjet nozzle driven by double piezo transducers has been developed to control pressure wave inside the nozzle more precisely. By monitoring maximum extrusion of meniscus, the optimum pulse width for each piezo transducer was measured, respectively. The different position of the piezo transducers on a single square channel accounts for the difference in optimum pulse width. In the present study, the bipolar waveform was applied to the front and rear piezo transducers. Then, two kinds of waveform combination are tested in order to investigate how they affect the ejected droplet speed. The first is the center-aligned condition where the pulse width of the rear piezo transducer is controlled as parameter. The results show that the maximum droplet speed occurs near its optimum pulse width. The second is that the relative time delay of the rear to front piezo pulses is varied. In this test, the maximum droplet speed is found when both the pulses are center-aligned. Thus, it is concluded that the most efficient driving waveform for the double piezo actuators is the center-aligned condition with the optimum pulse widths

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