Controlling Droplet Behaviour and Quality of DoD inkjet Printer by Designing Actuation Waveform for Multi-Drop Method

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Abstract. There are two techniques that can be used to improve the print quality of an inkjet printer, namely binary and greyscale techniques. In the greyscale technique, the method used is the multi drop ejection method. In the multidrop ejection method, it is more difficult to control droplet behaviour because the possibility of residual vibration and crosstalk will be higher, which can cause satellites and ligaments that can make poor print quality. In this study, we reveal how to control droplet behaviour in a multidrop ejection method so that it can produce good quality droplets. The comparison of droplet image that generated from basic waveform with the waveform using preliminary and suppressing vibration, without and with adjustments of actuation voltage was also studied.

Keywords: Waveform design, DoD inkjet printer, print quality, multi-drop

1.1. Introduction

The development of inkjet technology has been increasing rapidly. Its extensive use makes this technology continuously to be developed to improve printing quality. The fundamentals element in inkjet technology are ink formulation, print-head and print-surface. The printhead of inkjet printer actuated by the waveform with appropriate voltage and frequency for ejecting the droplet from the nozzle. The printing quality is closely related to the droplet quality, such as droplet shape, size and velocity [1]. The expected droplet is the droplet without satellite, ligament, or weeping occurrence. The droplet behavior is highly determined by the characteristics of the ink and the actuation waveform [2]. The actuation waveform influences the droplet ejection process, shape, volume and velocity. The proper design of input waveform must be made to get the optimum result [3] [4]. Some studies were conducted to design the actuating waveform, and or investigate the effect of waveform design on droplet performance [5], [6], [7] and [8].

It is important to control the droplet behavior for achieving high print quality. The different droplet shape performance is shown in Figure 1. This figure shows the spherical droplet as a good droplet shape, the droplet with satellite and ligament for the bad one. The other figure shows the
ligament with weeping occurrence. If the satellite and ligaments are formed during the process and it cannot merge to the main drop, then it may impact to the misshaping the printed dot on the substrate. The misshaping of the printed dot is described in Fig. 2. It shown that the main droplet that is followed by satellite and ligament, or when there is weeping occurrence, will affect to the final shape of the drop on the substrate. It will influence the final print quality, especially for the fine image that need high accuracy.

One of big challenges in inkjet technology is to generate the droplet with good performance, which is ejected without satellite and ligament existence. The satellite on droplet is unacceptable in some inkjet printer application and necessary to eliminate for high print quality [9]. Satellite is a main drop followed by one or more smaller drops. For controlling the droplet satellite is not easy but necessary for generate high-quality printing. Some studies studies observed the satellite formation [10], [11], [12] [13] and [14]. However, the study about eliminating the satellite effect is still limited, particularly for multi-drop ejection method. In this study, we will discuss about controlling the droplet behavior especially for multi-drop ejection method.
In inkjet technology, there are two kinds of ejection methods, namely binary and grey scale. Print quality related to the droplet size can be improved by using 2 techniques. First, by using a larger number of smaller drops at a higher resolution (the droplet is only produced in one size, called as binary printer or binary printing technique) \cite{15}. The smaller droplet can improve the resolution by higher dpi (dot per inch). Second way is by using grey-scale printing technique, which is each nozzle used to print a range of different droplet sizes. The edges of an image can be formed more precisely with a higher resolution. The higher resolution with binary technique provides the drop positioned flexibility, but need a higher nozzle density. Grey-scale printing technique can improve print quality and flexibility without changing the print resolution. In this study, we used multi drop ejection method as the greyscale technique. Study about multi-drop ejection method is still limited.

1.2. Droplet observation by IJ DOT

The experiment was carried out by using a droplet observation system GEN 5. The ejection signal was sent from personal computer to the print-head to generate the droplet and release it from the nozzle. The print-head type was piezoelectric D33. The droplet was observed, and its image was taken by CCD camera that equipped with iDS CMOS sensor and strobe lights. The mechanism of piezoelectric type was pull-push method. The experimental device is shown in Figure 3.

![Figure 3. Experimental Devices](image)

3. Single and Multidrop method with basic waveform

Basic waveform is the waveform design that was recommended by the printhead manufacturer to operate the printhead. The basic waveform using period 8 µs with $t_{\text{down}}$, $t_{\text{keep}}$, $t_{\text{up}}$ and $t_{\text{wait}}$ is 2 µs. Controlling droplet behaviour in multi-drop ejection methods is much more difficult than single droplet. Figure 5 shows the different result of different number of pulses using basic waveform design, for the same head temperature and actuation voltage. The head temperature used was 25°C and 14 volt actuation voltage and fire frequency was 1 kHz. The figures depict that more pulse applied to the printhead to generate the multi droplet that will be combined at the final stage, the satellite and ligament will be appear. If we applied the higher voltage, the longer ligament will be generated, and the distance between main droplet with satellite will be farther. The worse condition, weeping on printhead will be occurred.
| Number of main pulse (basic waveform) | Droplet appearance |
|-------------------------------------|--------------------|
| 1 pulse                             | ![Droplet appearance](image1) |
| 2 pulses                            | ![Droplet appearance](image2) |
| 3 pulses                            | ![Droplet appearance](image3) |
| 4 pulses                            | ![Droplet appearance](image4) |
| 5 pulses                            | ![Droplet appearance](image5) |

Figure 4. Droplet appearance of basic waveform (single and multidrop ejection method)

4. Result and Analysis

It was stated that the performance of inkjet print-head is mainly affected by residual vibration occurrence [16], [17], [18], and [19]. The residual vibration and crosstalk influence each other particularly in high drop repetition rate. This problem can cause the very large difference in droplet
speed [20] and [21]. The actuation waveform of the piezoelectric (PZT) element has a strong influence on the droplet ejection process, controlling both the size and velocity of the ejected droplets. For reducing the residual vibration that caused satellite, the actuating waveform to eject the droplet must be properly designed [22].

1. Long ligament: higher voltage will generate longer ligament.
   Hypothesis: Pull-push mode of PZT driving pulse caused water gun effect.
2. Satellite: if latest ejected drop cannot reach and merged to the prior drop or main drop.
   Hypothesis: residual vibration, and the difference of each drop velocity
3. Weeping occurrence
   Hypothesis: Excessive pressure from high voltage or high pressure, and by residual vibration.

Furthermore, the hypothesis how to overcome the cause of problems as stated above, was summarized as follows:

1. Caused: Water gun effect
   Solution: Create the preliminary vibration that able to be functioned as back pressure to “hold” or withstand the high pressure.
2. Caused: Residual vibration
   Solution:
   - Determine the suitable period from each pulse that able to reduce the residual vibration by wave superposition concept.
   - Obtain the appropriate voltage for each drop to adjust the speed so then it can be merged before reach the substrate. Note that the larger voltage will generate the higher speed.
3. Weeping occurrence
   Solution: Same solution as water gun effect and residual vibration, and determine the limit of applied voltage to prevent the excessive pressure. The illustration of problem and hypothesis is shown in Figures 5 and 6.

First step in designing new waveform with optimum result as the objective of this study is in finding the basic concept to eliminate the “water gun” effect for generating the multi-drop concept. Next step is determining how to reduce the residual vibration for prevent the satellite and weeping occurrence, particularly in the multi-drop concept. The preliminary vibration is the additional front pulse such as the main pulse with low voltage without droplet ejection, that is used to accelerate the droplet velocity and increase the volume. On another side, suppressing vibration is the small additional pulse after main pulse, to reduce the residual vibration and affect the reduction of droplet speed and volume. From previous experiment, it is determined that the applied voltage that effective to accelerate the droplet speed is 30% of base voltage. On the other side, the suppressing vibration is able reduce the droplet volume and speed, by reducing the residual vibration. The effective pulse as suppressing vibration is with the input parameter for $t_{\text{down}}$, $t_{\text{keep}}$, and $t_{\text{up}}$ respectively 1μs with $t_{\text{wait}}$ from main pulse 0 μs.
It was stated that small negative pressure as preliminary vibration can prevent the weeping occurrence, but there is no explanation about the mechanism of how the negative waveform can avoid the weeping. Small pressure implies that there is no droplet ejection. It was also stated that the long dwell time ($t_{\text{keep}}$) can generate the large back pressure. The same author in other study, concluded that the effective dwell time for suppressing the satellite effect is longer than efficient dwell time, but it may result in no jetting droplet. The previous study that was investigate the effect of preliminary and
suppressing vibration shows that it will control the droplet behavior, both speed, volume, and shape [23]. It was found that by using the input parameter respectively as the preliminary vibration give a better result in generating the clear spherical droplet. The other idea in creating the large back pressure is by combining the preliminary and suppressing vibration [24]. By overlapping that two pulses and 4μs shifted period, then we can create the large voltage without drop ejection. The concept generation of other preliminary vibration for creating the large back pressure is shown in Figure 7. This waveform that generated from two overlapped pulses with input parameter $t_{\text{down}} - t_{\text{keep}} - t_{\text{up}}$ respectively 2μs, 2 μs, 1 μs (50% adjusted voltage), then $t_{\text{wait}}$ 0 μs, following by the next pulse with $t_{\text{down}} - t_{\text{keep}} - t_{\text{up}}$ respectively 2μs for each parameter. The shape of waveform similar with alphabet “W” so called as “W” preliminary vibration. The effectiveness of this preliminary vibration on multi drop ejection method can be seen on figures 8 – 10. Figure 8 depicts the multidrop ejection method using basic waveform (Figure 8a). The droplet generated with long ligament on 14 volt of actuation voltage (Figure 8b). Furthermore, if using a larger voltage, both satellite and ligament are appeared (Figure 8c).

In accordance with the concept discussed in Figure 7, that in the multi drop ejection method, we must ensure that the droplet that is issued later must have a higher speed than the previous droplet. It is intended so that the droplet can reach the previous droplets, and unite to produce a completely round droplet, without satellite and ligaments. Hence, we must adjust the speed of the droplet in accordance with the order in each pulse, by applying different voltages so that the resulting pressure is different. Greater voltage will push the droplet out harder so that the resulting speed will be higher, compared with a lower actuation voltage. In addition, the adjustment of the applied voltage must also be ensured so that the final results in superposition of waves that produce residual vibrations do not exceed negative waves or back pressure which serves to withstand excessive pressure due to the watergun effect. Comparison of the results of droplets that use waveform design without voltage adjustments with those using adjustments in voltage can be seen in the Figure 9. The adjustment provided is to make a voltage difference of 2% greater for the next pulse.
Conclusion

It is very important to control droplet behavior. The way that can be done is to make a proper waveform design. Through literature reviews and experiments carried out coincide with evaluation and observation of droplet behavior with various wave designs, particularly in the multi drop ejection method, it can be concluded that the ways in controlling droplet behavior are as follows:

1. Using preliminary vibration with a W shape which functions to generate back pressure that can withstand the water gun effect.
2. Additional suppressing vibration at the end of the waveform to reduce residual vibration and cross talk.
3. Making adjustments to each pulse in the multi drop ejection method in such a way that the later droplet velocity released has a higher speed than the previous one.

Figure 8. Multi-drop ejection method (5 pulse, basic waveform)
(a) waveform design  (b) 14 volt actuation voltage  (c) 15 volt actuation voltage
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Reference

[1] W. Hsuan-Chung and L. Huey-Jiuan, "Effects of Actuating Pressure Waveforms on the Droplet Behavior in a Piezoelectric Inkjet," Materials Transactions, vol. 51, no. 12, pp. 2269-2276, 2010.

[2] K. Sarah, S. Chris and H. Ulrich, "The effect of viscosity and surface tension on inkjet printed picoliter dots†," RSC Advances, vol. 9, p. 31708–31719, 2019.

[3] K.-S. Kwon, "Experimental analysis of waveform effects on satellite and ligament behavior via in situ measurement of the drop-on-demand drop formation curve and the instantaneous jetting speed curve," JOURNAL OF MICROMECHANICS AND MICROENGINEERING, vol. 20, pp. 1-14, 2010.

[4] K.-S. Kwon, "Waveform Design Methods for Piezo Inkjet Dispensers Based on Measured Meniscus Motion," JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, vol. 18, no. 5, pp. 1118-1125, 2009.

[5] W. Hongfang, X. Xiaolei, Y. Zhifu, Y. Maocong and Z. Helin, "A waveform design method for high DPI piezoelectric inkjet print-head based on numerical simulation," Microsystem Technologies, vol. 2017, p. 5365–5373, 2003.

[6] H. C Leigh, H. Yong and C. Wenzxuan, "Performance evaluation of bipolar and tripolar excitations during nozzle-jetting-based alginate microsphere fabrication," JOURNAL OF MICROMECHANICS AND MICROENGINEERING, vol. 22, pp. 1-11, 2012.
[7] W. Hsuan-Chung, S. Tzu-Ray, H. Weng-Sing and L. Huey-Jiuan, "Study of Micro-Droplet Behavior for a Piezoelectric Inkjet Printing Device Using a Single Pulse Voltage Pattern," *Materials Transactions*, vol. 45, no. 5, pp. 1794-1801, 2004.

[8] K. Amol A., B. Xavier, S. Gérard, B. Robert, K. Sjirk and d. Z. Wim, "A Waveform Design Method for a Piezo Inkjet Printhead Based on Robust Feedforward Control," *JOURNAL OF MICROELECTROMECHANICAL SYSTEMS*, vol. 21, no. 6, pp. 1365-1374, 2012.

[9] K. Amol A., B. Xavier, B. Robert, W. Herman and W. Rene’, "Performance improvement of a drop-on-demand inkjet printhead using an optimization-based feedforward control method," *Control Engineering Practice*, vol. 19, pp. 331-338, 2008.

[10] S. Pyungho, S. Jaeyong and L. Myeong Ho, "Control of droplet formation for low viscosity fluid by double waveforms applied to a piezoelectric inkjet nozzle," *Microelectronics Reliability*, vol. 51, p. 797–804, 2011.

[11] Z. Hai-yun, W. Jin and L. Guo-dong, "Numerical investigation of the influence of companion drops on drop-on-demand ink jetting," *Journal of Zhejiang University SCIENCE A volume*, vol. 13, p. 584–595, 2012.

[12] T. Ming-Hsiu and H. Weng-Sing, "Effects of Pulse Voltage on the Droplet Formation of Alcohol and Ethylene Glycol in a Piezoelectric Inkjet Printing Process with Bipolar Pulse," *Materials Transactions*, vol. 49, no. 2, pp. 331-338, 2008.

[13] M. Graham D., H. Stephen Daniel and H. Ian M., "Inkjet printing - The physics of manipulating liquid jets and drops," *Journal of Physics Conference Series*, vol. 105, no. 1, pp. 1-14, 2008.

[14] J. Byoung Wook, L. Ayoung, A. Kyung Hyun and L. Seung Jong, "Evaluation of jet performance in drop-on-demand (DOD) inkjet printing," *Korean Journal of Chemical Engineering*, vol. 26, no. 2, pp. 339-348, 2009.

[15] H. Ian M. and M. Graham D., Inkjet Technology for Digital Fabrication, United Kingdom: John Wiley & Sons Ltd, 2013.

[16] K. Byung-Hun, K. Sang-II, L. Jae-Chang, S. Seung-Joo and K. Seong-Jin, "Dynamic characteristics of a piezoelectric driven inkjet printhead fabricated using MEMS technology," *Sensors and Actuators A: Physical*, vol. 173, no. 1, pp. 244-253, 2012.

[17] K. Amol A., B. Xavier, S. Gérard, B. Robert, K. Sjirk and d. Z. Wim, "A Waveform Design Method for a Piezo Inkjet Printhead Based on Robust Feedforward Control," *JOURNAL OF MICROELECTROMECHANICAL SYSTEMS*, vol. 21, no. 6, pp. 1365-1374, 2012.

[18] B. David and T. F.E., "Experimental and Theoretical Study of Wave Propagation Phenomena in Drop-on-Demand Ink Jet Devices," *IBM J. RES. DEVELOP.* , vol. 28, no. 3, pp. 314-321, 1984.

[19] E. M., v. d. B. P.P.J. and W. S., "Improving the Performance of an Inkjet Printhead using Model Predictive Control," in *18th IFAC World Congress*, Milano (Italy), 2011.

[20] K. Jan G., S. Patrick J. and S. Dong-Youn, Inkjet-based Micromanufacturing, Weinheim, Germany: Wiley-VCH Verlag & Co. KGaA, 2012.

[21] E. M., v. d. B. P.P.J. and W. S., "Experimental-based feedforward control for a DoD inkjet printhead," *Control Engineering Practice*, vol. 21, pp. 940-952, 2013.

[22] K. Kye-Si, "Waveform Design Methods for Piezo Inkjet Dispensers Based on Measured Meniscus Motion," *JOURNAL OF MICROELECTROMECHANICAL SYSTEMS*, vol. 18, no. 5, pp. 1118-1125, 2009.

[23] O. Oke, H. Shigeyuki, I. Yoshie and D. Zefry, "Effect of Front and Back Suppressing Vibration on Actuation Waveform Design of DoD Inkjet Printer to Droplet Speed and Volume," *Universal Journal of Mechanical Engineering*, vol. 7, no. 6B, pp. 12-18, 2019.

[24] O. Oke, K. Tadayuki, H. Shigeyuki and K. Ken, "New actuation waveform design of DoD inkjet printer for single and multi-drop ejection method," *Additive Manufacturing*, vol. 25, pp. 552-531, 2019.

[25] D. T and J. R, "Drop Formation in Inkjet Printing," in *Fundamentals of Inkjet Printing: The Science of Inkjet and Droplets*, Wiley-VCH , 2016, pp. 93-115.