Inkjet status monitoring using meniscus measurement

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Abstract

Meniscus motion measurement techniques have been developed such that the jetting condition in a piezo inkjet head can be monitored. Acquired CCD camera images, where a strobe light from an LED (Light Emitting Diode) was synchronized by the jetting signal, were used to measure the meniscus motion. For efficient image processing of the acquired images, a straight line near the nozzle in the jetting direction was used for defining the ROI (Region of Interest). Then, the meniscus location can be identified from the discontinuity that exists in the pixel intensities along the ROI in the image. Finally, it was shown from the experimental results that the measured meniscus can predict jetting behavior without actual jetting.

Introduction

Inkjet printing makes use of ink droplets to form required patterns on a substrate. By using inkjet printing technology, the volume of a droplet from the inkjet printhead can be controlled to an accuracy of picolitres. In addition, the droplet can be placed onto the substrate to an accuracy of micrometers. Due to these features, inkjet technology has recently emerged as one of the most powerful tools for patterning electronics devices, such as large area display applications, RFID (Radio Frequency Identification), PCB (Printed Circuit Board) patterning, etc [1,2].

Various types of jetting materials may be needed to be jetted as the application of inkjet printing broadens. The material properties needed for jetting have been discussed in previous works [3, 4]. The jetting performance should be well controlled once materials are found to be jettable from an inkjet head in order for this inkjet technology to be viable for various industry applications. In practice, the waveform voltage for driving the print head has been used in order to control speed or volume of the ink droplet [5, 6]. However, the conventional process for designing an optimal waveform requires a significant number of experiments because it is based on experimental results of the droplet speed versus the waveform relationship [5, 6]. Furthermore, the trial and error search should be used for finding the jetting conditions when there is no jetting from the inkjet head. Therefore, it may require a lot of effort to find the optimal waveform with the conventional method, especially when a new jetting material is used.

The jetting phenomena have been known to be related to the pressure wave inside the inkjet head [7]. In Bogy's work [7], the meniscus protrusion images were used to explain the pressure wave behavior in relation to the waveform design. However, automatic measurement techniques for meniscus motion might be needed for practical applications since Bogy's work was based on manual post-processing of a large number of CCD images. Recently, the meniscus motion on the inkjet nozzle was measured by using PIV techniques [8, 9]. Jetting behavior can be understood using these visualization techniques. However, this requires that additional particles be included in the jetting material for the PIV measurements, which might affect the jetting performance. This technique also requires special equipment for measuring the particle velocities. Therefore, the meniscus motion measurement using PIV techniques might be difficult to implement in many practical applications.

This study proposes a new method for measuring the meniscus motion in order to find the optimal waveform, where actual jetting from the nozzle is not required. The proposed meniscus measurement technique is based on using CCD camera images where LED lights were synchronized with the jetting signal. The proposed method does not require any special hardware, unlike the previous methods using PIV techniques, since most printing systems already have a CCD camera system with a strobe LED for measuring the droplet speed. From the meniscus motion, ink properties in the print head such as viscosity and the speed of sound can also be measured. Furthermore, systematic waveform design can be possible without actual jetting since the meniscus motion is related to the pressure wave behavior at the nozzle. It should be noted that the meniscus motion is subject to the jetting condition. Therefore, once the waveform is designed, the meniscus motion can also be used as a monitoring tool for detecting any abnormal conditions in the system by comparing it with the meniscus motion measured during normal jetting status.

Pressure wave inside the piezo dispenser

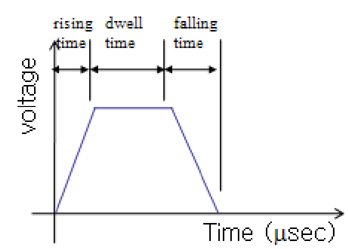

Figure 1. Typical waveform for the piezo inkjet.

Fig. 1 shows a typical waveform used to drive the piezo in the inkjet dispenser. The first rising step of the waveform results in an expansion of the piezo dispenser and the subsequent falling step of the waveform results in a contraction of this piezo dispenser, and this can be seen in Fig. 2. When the rising (or falling) step of the waveform was applied, the two negative (or positive) pressure waves started to propagate in opposite directions from the center where the piezo is located. Part of the pressure wave is transmitted and part of it is reflected due to the boundary conditions of the piezo tube when the traveling pressure waves meet an obstruction [7]. The boundary condition of the ink supply part can be considered to be ideally open because the diameter of the supply part is larger than that of the inkjet dispenser. The pressure wave reflects with an opposite sign when the traveling pressure wave meets an open end. On the other hand, if the pressure wave reaches the nozzle side, the boundary condition can be modeled as an ideally closed condition since the nozzle area is small. The pressure wave retains its sign when reflecting in this case.

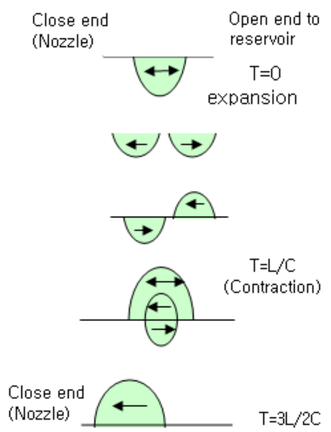

Figure 2. Pressure wave inside a print head.

The time between the expansion and the contraction is referred to as the dwell time. The optimum dwell time of L/C, where L is dispenser tube length and C is the speed of sound, was recommended such that the contraction cancels out the reflected negative wave and doubles the magnitude of the reflected positive pressure wave. Then, at a time of 3L/2C after the initial expansion, the positive pressure wave reaches the nozzle and the ink droplet will be ejected. Residual pressure waves that have damped vibration characteristics exist even after jetting. The residual pressure waves have information about the jetting conditions as well as the ink properties such as viscosity and the speed of sound.

Status monitoring using the measured meniscus motion

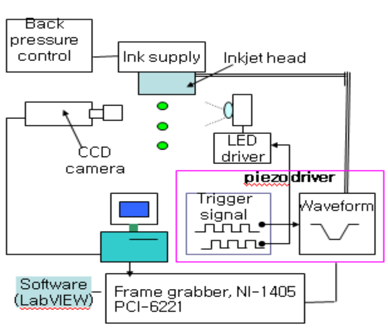

Figure 3. CCD camera system with a strobe LED.

In this paper, meniscus protrusion was measured automatically by the use of a CCD camera system with a strobe LED. Fig. 3 shows the experimental setup for acquiring CCD camera images in order to measure the meniscus motion. LabVIEW software was developed in this research in order to generate the designed waveform data and send it to an arbitrary waveform generator (Agilent 33220A) via a GPIB (General Purpose Interface Bus). The waveform data, stored in the memory of the waveform generator, waits for trigger signals to generate the desired waveform. A TREK PZT drive (PZD350) was used as the print head driver to amplify the waveform voltage generated from the arbitrary waveform generator by 100 times. This work also used the two counters in the multi-function IO unit (a NI PCI-6221) in order to generate two digital pulse trains, as is shown in Fig. 4. The first digital pulse train in Fig. 4(a) is used as a trigger signal for generating the waveform for the jetting, and the second pulse train in Fig. 4(b) or (c) is used for controlling the LED light. The ink jetting frequency can be controlled by the first digital pulse train, while the second pulse was triggered from the first pulse. Here, the delay time between the first and second pulse can be adjusted either manually or automatically via an algorithm. The meniscus at the delayed time can appear to be frozen in the image due to the time delay in the second pulse. Here, the duty ratio of the second pulse seen in Fig. 4(b) or (c) can change the image brightness by varying the light intensity of the LED.

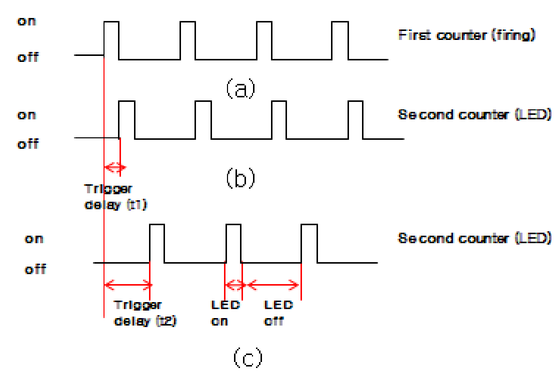

Figure 4 Time delay for the LED with respect to jetting signal.

Figs. 5 and 6 show the software developed in order to measure the meniscus motion. Nano silver ink, with nanoparticles of approximately 10 nm diameter dissolved in DI (De-Ionized) water (20wt %), was used as a jetting material in the experiment. A straight line ROI (Region Of Interest) generated near the nozzle in the jetting direction was used for identifying the meniscus location from the acquired image. Then, the meniscus location can be identified from the discontinuity in the pixel intensities along the ROI in the acquired image. The ROI line consists of image pixels having values that vary from 0 to 255 according to the brightness of the image. The meniscus locations can be detected by setting a suitable threshold value where the image pixel values in the ROI will cross the threshold value. The identified meniscus location was verified in the developed software by overlaying the cross-line at the meniscus location to verify the result in the CCD camera images, as is seen in Figs. 5 and 6. In order to understand meniscus behavior after jetting signal, each meniscus location should be identified with respect to the pre-determined time delays in LED lights, which are synchronized to the jetting signals.

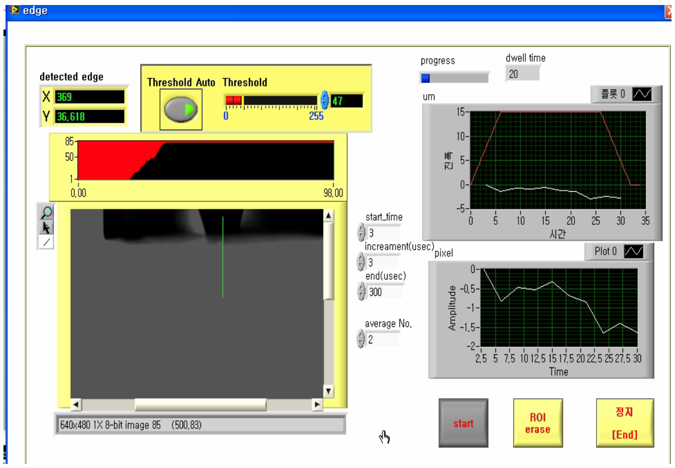

Figure 5. Meniscus location at a 30 μsec trigger delay.

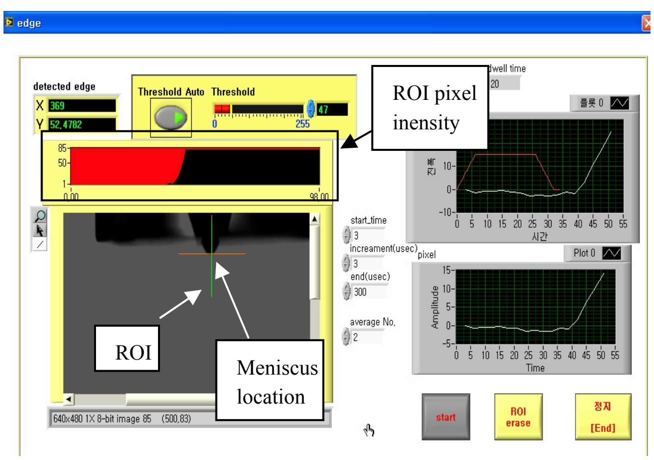

Figure 6. Meniscus location at a 50 μsec trigger delay.

Figs. 5 and 6 show the acquired images and measured meniscus locations when the trigger delays of the LED with respect to the jetting signal were t_1=30 μsec and t2=50 μsec. Here, the meniscus motion was repeated with a frequency of 1 kHz because the trigger signals for generating the waveform were set to 1 kHz, but the meniscus appears to be a frozen image, as is seen in Figs. 5 and 6, due to the strobe LED lights that are synchronized with the jetting signal. The trigger delay for the LED lights is increased from the starting time to the end time by pre-determined steps in order to scan the meniscus locations throughout the time of interest after the driving waveform voltage signal is applied. Note that the jetting voltage should be kept low such that actual jetting does not occur in order to measure the meniscus motion. The strength of the pressure wave at the nozzle can increase according to the increase in the driving voltage, which allows jetting phenomena such as the satellite forming and ink break-off behavior from the nozzle to be observed by visual means.

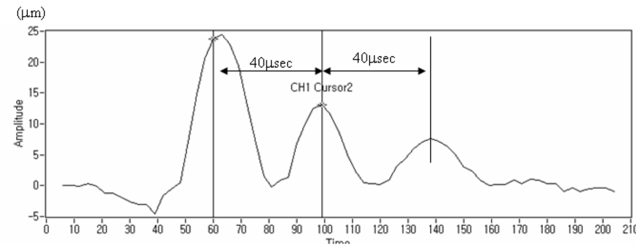

Figure 7. Meniscus motion with a dwell time of 20 μsec (15 volts).

Fig. 7 shows the measured meniscus motion when an amplitude of 15 volts and a dwell time of 20 μsec was used for the waveform shown in Fig. 1. The initial time delay for the LED light was 5 μsec and this time delay increased in 5 μsec intervals until the final time delay of the LED light became 200 μsec. A total of 40 meniscus locations were used in this example in order to properly understand the meniscus behavior. This process may require a significant processing time of up to tens of seconds depending on the required number of meniscus locations. Therefore, it should be noted that the proper maintenance scheme such as purging and wiping might be required during the meniscus measurement process in the case of using fast drying ink, since fast drying ink often causes clogging conditions at the nozzle. As is seen in Fig. 7, the meniscus motion shows a residual pressure wave that has a period of time and an exponentially decaying form as time increases. Here, the measured meniscus motion can be characterized by a damped vibration equation as

$$y = Ae^{-\xi\omega_n t}\sin(\omega_d t + \phi) \qquad (1)$$

where it can be assumed that the frequencies, ω_n and ω_d, which have units of rad/sec, have approximately equal values when the damping ratio, ξ,, is small. Here, peak amplitude is denoted as *A*, where larger peak amplitude indicates stronger pressure for jetting the ink. A higher damping ratio (i.e., larger ξ) indicates a higher viscosity of the ink, and a smaller period (i.e., larger ω_n or ω_d) indicates a faster speed of sound for the ink. Therefore, the ink properties such as viscosity and the speed of sound can be understood.

For the comparison study, the speed of droplet was measured as seen in Fig. 8 according to the dwell time when the voltage was fixed at 35 volts. The relationship between the droplet speed and dwell time shown in Fig. 8 has been widely used for both waveform design and an understanding of jetting behavior [6]. From the results in Fig. 8, the jetting speed has peaks with a period of 40 μsec with respect to the dwell time. The optimal dwell time should be designed to be 20 μsec when the maximum speed is obtained. The droplet speed becomes less affected by dwell time as the dwell time increases because the effect of the rising voltage becomes damped out before the falling voltage is applied due to the viscosity effect of the ink.

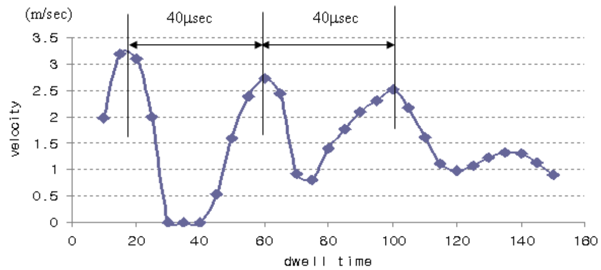

Figure 8. Droplet speed vs. dwell time relationship.

Unlike the conventional method using droplet speed, the proposed method using meniscus motion does not require any actual jetting in order to predict the jetting behavior shown in Fig. 8. Note that the period of the meniscus motion in Fig. 7 was about 40 µsec, which is in agreement with the results shown in Fig. 8. The decaying rate of the meniscus motion in Fig. 7 is also in good agreement with the results in Fig. 8, confirming that the jetting behavior can be predicted by the meniscus measurement. The waveform in Fig. 1 can then be designed by using the measured meniscus motion, without the need for a time consuming experiment to obtain the speed and dwell time relationship. Additionally, it is easily understood from the meniscus motion in Fig. 7, that the droplet will be ejected from the nozzle 60 µsec after the jetting signal is applied. It is also easily understood from the meniscus motion that the positive pressure waves at 100 µsec and 140 µsec may result in satellite drops, which should be avoided in practical applications. Such phenomena are difficult to understand from the conventional experimental results shown in Fig. 8.

Conclusions and discussions

Meniscus measurement techniques have been developed in order to understand the jetting conditions in an inkjet print head. The meniscus motion measurement utilizes the acquired CCD camera images where the LED light is synchronized with the jetting signal. Therefore, the proposed measurement method does not require any special measurement equipment since most inkjet printing systems have a CCD camera system with a strobe LED for droplet speed measurement. The proposed method has advantages since the jetting behavior can be predicted without the need for actual jetting. Furthermore, the ink properties such as viscosity and the speed of sound can be understood from the vibration characteristics of the meniscus motion. The systematic algorithm to obtain a proper waveform design is currently under development based on the measured meniscus motions.

References

[1] K.S. Kwon and W. Kim, "A waveform design method for high speed inkjet printing based on self-sensing measurement," Sensors and Actuators A, 140, pg. 75. (2007).
[2] T. Gohda, et al., A 3.6-in 202-ppi Full-color AMPLED Display Fabricated by Ink-jet method, SID 2006 (2006).
[3] J.E. Fromm, "Numerical Calculation of the Fluid Dynamics of Drop-on-Demand Jets," IBM J. Research Development, 28, 3 (1984).
[4] R. Nuno, C. Ainsley and B. Derby, "Ink-jet delivery of particle suspensions by piezoelectric droplet ejectors," Journal of applied physics, 97, 094903 (2005).
[5] Microfab technote, Drive waveform effects on ink-jet device performance, 99-03 (1999).
[6] Szczech J.B., Magaridis C.M., Gamota D.R., "Fine-line Conductor Manufacturing Using Drop-On-Demand PZT Printing Technology", IEEE Transactions on Electronics packaging manufacturing, 25, 1 (2002).
[7] D.B. Bogy and F.E. Talke, "Experimental and theoretical study of wave propagation phenomena in drop-on-demand ink jet devices," IBM Journal of research and development, 28, 3, pg. 314. (1984).
[8] B.Beulen, et al., "Flows on the nozzle plate of an inkjet printhead," Exp Fluids, 42, pg. 217. (2007).
[9] C.D. Meinhart and H. Zhang, "The Flow Structure inside a microfabricated inkjet printhead," Journal of microelectromechanical systems, 9, 1 (2000).

Author Biography

Kye-Si Kwon has been an assistant professor at Soonchunhyang University in Korea in the department of mechanical engineering since 2006. He received his BS degree in mechanical engineering from Yonsei University, Seoul, Korea in 1992. He holds a master's degree (1994) and a PhD (1999), both in mechanical engineering from KAIST, Korea. Before joining Soonchunyang University, he was a member of the research staff at the Samsung Advanced Institute of Technology. His current work is focused on the development of intelligent ink jetting systems.