A Vision Measurement Technique for Evaluation of Pulse Voltage Effect on Electrohydrodynamic (EHD) Jet

Kye-Si Kwon, Min-Hyuck Jang and Hyeong Rae Roh
Department of Mechanical Engineering, Soonchunhyang University, Chungnam, Korea
Jung-Kook Go
Department of Electrical & Robot Engineering, Soonchunhyang University, Chungnam, Korea

Abstract

In this paper, we present a vision measurement technique to evaluate electrohydrodynamic (EHD) inkjet behavior, and discuss the effects of the pulse voltage shape on the EHD jets for drop-on-demand printing, including the falling and rising time in the pulse voltage. Sequential images acquired by a charge-coupled device (CCD) camera with a strobe light-emitting diode (LED) were used to visualize EHD jet behavior with respect to time. A vision algorithm was implemented in an EHD jet system to enable in-situ measurement and analysis of EHD jets. A guideline for selecting pulse shape parameters is also presented, to enable the achievement of reliable jets for drop-on-demand printing.

Introduction

The application of inkjet technology has been broadening from home printers to manufacturing tools. Recently, there have been demands for high-resolution printing, especially in the field of printed electronics applications. However, the droplet volumes of 1~2 picoliters (pL) produced with nozzle diameters of 16 μm limit current inkjet technology [1]. As an alternative technique for fine printing, electrohydrodynamic (EHD) inkjet technology has recently been drawing attention, because it has advantages over conventional inkjet pattern method, in that droplets smaller than the nozzle diameter can be ejected, and materials with wider viscosity range could be used for jetting. Successful direct printing of a few microns of conductive lines in width has been reported using the technology [1-3].

To use EHD jets in drop-on-demand printing applications, each pulse voltage should produce a single droplet. To optimize the pulse voltage, it is important to understand the jet behavior in relation to the shape of the pulsed voltage. In particular, the jet start time needs to be understood with respect to the pulse voltage. The jet start time should remain the same irrespective of jet frequency. Otherwise, jet placement error may occur, because the motion stages for the head or the substrate move during drop-on-demand printing.

CCD cameras with strobe LEDs have widely been used to measure jet behavior in conventional inkjet heads. In this work, the application of strobe LEDs is extended to EHD jet measurement. Sequential images using strobe LEDs are acquired to characterize the EHD jet behavior in relation to the pulse voltage.

The effects of the voltage pulse width and amplitude on the EHD jet have been investigated in previous studies [3]. However, it seems that general guidelines for determining pulse voltage parameters have not yet been established. Also, few published studies discuss the effects of pulse shape on EHD jets, including the rising and falling parts of the pulse. In this study, we investigate these effects based on the meniscus behavior measured in vision analysis. We found that the rising, falling, and dwell parts of the pulse voltage affected the EHD jet in different ways. By changing the pulse shape, the jet starting time and jet duration can be adjusted.

Vision measurement technique and image analysis

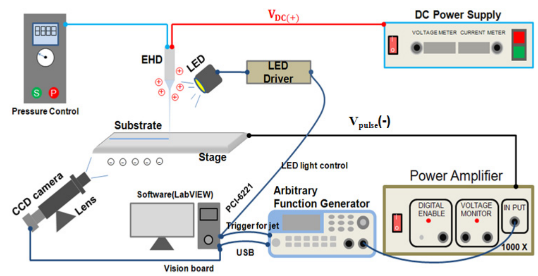

***Figure 1**. Schematic of EHD jet system.*

Fig. 1 shows a schematic and photo of the EHD jet system developed for the visualization of jet images and for printing. To visualize the jet images, LED lights were synchronized with respect to jet triggers.

To visualize the jet images, LED lights were synchronized with respect to jet triggers. Two digital pulse trains from a counter board (PCI-6221, NI, USA) are used for the synchronization. The first digital pulse train is used as a trigger signal to generate the pulse voltage. The second pulse train is used to control the LED light. The second pulse is triggered from the first pulse. The trigger delay time between the first pulse and second pulse is adjusted such that the jet image at the delayed time can appear to be frozen in the acquired image.

Fig. 2 shows selected sequential images of an EHD jet measured using the strobe LED. As shown in Fig. 2, a pulsating EHD jet can be analyzed in relation to pulse voltage.

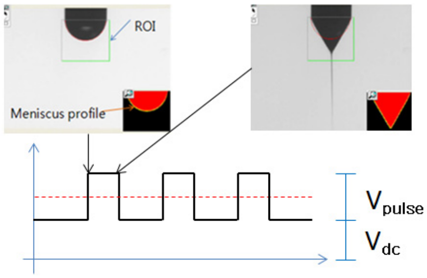

***Figure 2**. Pulse voltage effects on EHD jet*

The EHD inkjet drop formation is quite different from that of a conventional inkjet printhead. As shown in Fig. 3, the pulsating jet is difficult to analyze, because the shape of the jet is thin and very long. So, we analyze the extracted meniscus profile rather than directly analyzing the jet in flight, unlike conventional inkjet measurement.

The jet behavior was characterized by the meniscus height. The meniscus height used to evaluate the EHD jet is defined by the difference between a reference and the monitored maximum location of the meniscus profile in the downward direction, as shown in Fig. 3. The jet behavior of an EHD jet can be understood by the meniscus height variation with respect to time. For more information, video can be referenced in [4].

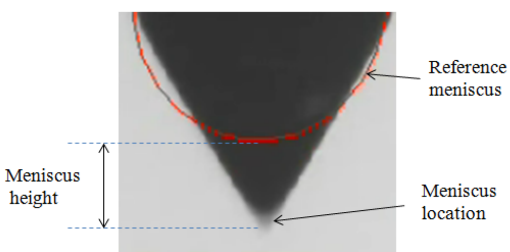

***Figure 2**. EHD jet analysis*

Pulse shape effect on EHD jet

In this section, the effects of pulse shape on the jet start time and jet frequency are mainly discussed, based on meniscus behaviors measured by our vision system as seen in Fig.3.

A simple trapezoidal pulse was considered as the driving pulse voltage, as shown in Fig. 4.

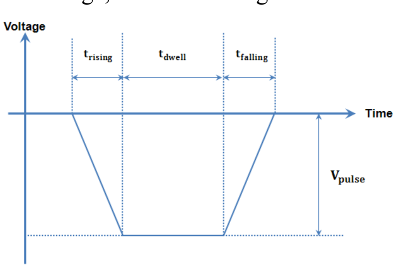

***Figure 4**. Pulse shape parameters*

Fig. 5 shows the meniscus behavior according to dwell time and jet frequency. The meniscus behavior was measured with respect to time using the proposed vision analysis methods. There is a range of dwell times to obtain stable pulsating EHD jets. For example, drop-on-demand jets are not possible if a dwell time of less than 0.1ms is used in our experiment. The minimum dwell time for the jet should be longer than 0.2ms, because the meniscus needs to be sufficiently pulled down to the substrate before it becomes a pulsating jet. On the other hand, if the dwell time is longer than 1 ms, irregular dripping is observed during the pulsed voltage. This irregular dripping cannot be used in printing applications. The EHD jet is normally initiated at the time of maximum meniscus height. As shown in Fig. 5, the jet starting time, t_{start}, is almost the same as the dwell time, i.e. $t_{start} \approx t_{dwell}$. This means that the jet starting time can be controlled easily through the dwell time.

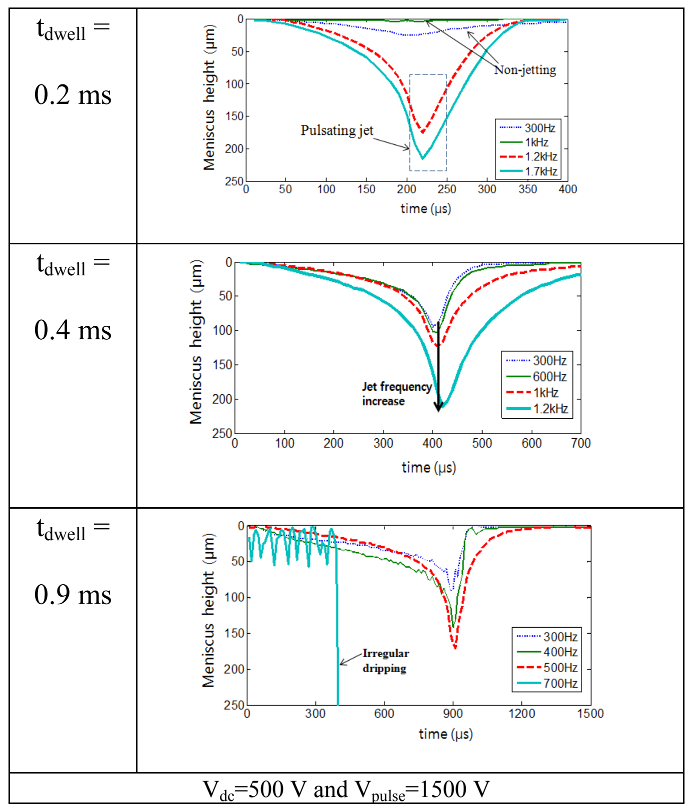

***Figure 5**. Pulse width (dwell time) effects on EHD jet*

To investigate the effect of rising time on EHD jet behavior, rising times of t_{rising}=0.1ms, 0.2ms, and 0.4ms were used. As shown in Fig. 6 (a), the jet starting time, t_{start}, is almost the same as the total length of a pulse:

$$t_{start} \approx t_{rising}+t_{dwell}. \qquad (1)$$

There may be an advantage in using the rising time, in that the meniscus behavior can be stable due to the gradual change in the meniscus location to the jet location. However, the total time required for a pulse voltage is longer than that of a simple pulse voltage using dwell time only, which might limit the maximum jet frequency

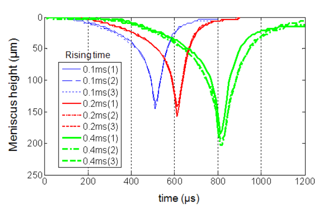	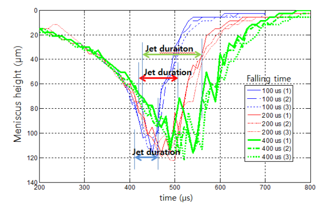
(a) Rising time effect ($t_{falling}$=0 ms, t_{dwell}=400 μs, V_{pulse}=1500 V, V_{dc}=500 V, f= 500 Hz)	(b) Falling time effects on meniscus behavior. (t_{dwell}=0.4ms, t_{rising}=0, V_{pulse}=1500V, V_{dc}=500V, f=500Hz)

***Figure 6**. Rising and falling time effects on EHD jet*

To investigate the effect of the falling time on EHD jets, the pulse voltages shape with falling times of $t_{falling}$=0.1, 0.2, and 0.4ms were used, and the other parameters were fixed at V_{pulse} =1500 V, V_{dc} =500 V, t_{dwell}=0.4 ms, t_{rising}=0 ms, and f= 500 Hz.

As shown in Fig. 6(b), the jet behavior effect of the falling time differed significantly from those of the other voltage parameters. It was found that the jet start time is related to the total length of the pulse in the case of $t_{falling}$ = 0 μs. . However, the jet start time might not correspond to the total length of time if the falling time is not zero. We observed in the experimental results in Fig. 6 (b) that the jet duration could be increased by using a longer falling time. For example, with a falling time of 0.4ms, the jet duration was increased to 150 μs. The jet duration could be less than 50 μs with zero falling time. In this way, the amount of jet can be adjusted by changing the jet duration.

The range for pulse parameters for a stable jet might differ according to the ink properties, nozzle diameter, stand-off distance (between the head nozzle and the substrate), and the fluid delivery systems. However, the effects of pulse shape on the EHD jet discussed in this study can be referenced when the optimal conditions for the EHD jet are found. These findings are based on experimental observation, and further theoretical studies might be needed to fully understand the jetting physics.

Conclusions

The voltage shape effect on EHD jets can be summarized as follows:

- The falling part of the pulsed voltage is important because a stable pulsating jet starts after this part is applied at either the nozzle or the substrate. The amount (or duration) of the jet can be adjusted slightly by the length of the falling time. However, zero falling time is recommended for drop-on-demand printing applications to produce a consistent pulsating jet for each jet trigger signal.
- The rising part of the pulse voltage accounts for the initial meniscus deformation. The use of rising time results in a gradual increase in the meniscus height. However, the use of a long rising time should be avoided, since the total time for the pulse voltage can increase. The total time for the pulse voltage should be minimized to increase the jet frequency.
- If the dwell time, t_{dwell}, is too short, there will be no jetting. However, if t_{dwell} is too long, then there will be inconsistent dripping of ink rather than stable pulsating jets. There is a range of t_{dwell} values for stable jets. Both the rising and dwell parts of the pulse voltage have similar effects, because they are related to the initial meniscus deformation as well as the jet start time. However, the use of t_{dwell} rather than t_{rising} is effective, because the time required for initial meniscus deformation can be shortened.

Acknowledgement

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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 measurement methods for controlling inkjet head.