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Evaluation method of inkjet first drop dissimilarity

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Abstract

Drop-on-demand inkjet printing has been used as a manufacturing tool for printed electronics, and it has several advantages since a droplet of an exact amount can be deposited on an exact location. Such technology requires positioning the inkjet head on the printing location without jetting, so a jetting pause (non-jetting) idle time is required. Nevertheless, the behavior of the first few drops after the non-jetting pause time is well known to be possibly different from that which occurs in the steady state. The abnormal behavior of the first few drops may result in serious problems regarding printing quality. Therefore, a proper evaluation of a first-droplet failure has become important for the inkjet industry. To this end, in this study we propose the use of a high-speed camera to evaluate first-drop dissimilarity. For this purpose, the image acquisition frame rate was determined to be an integer multiple of the jetting frequency, and in this manner, we can directly compare the droplet locations of each drop in order to characterize the first-drop dissimilarity

Introduction

The applicability of inkjet technology has increased from its use in home printers towards implementation as manufacturing tools. Drop-on-demand inkjet printing presents advantages over continuous inkjet printing because an ink droplet of an exact amount can be placed on an exact location without the use of any droplet deflection device. Jetting from a drop-on-demand inkjet head is not continuous because there is a non-jetting period (pause time) during the relative movement of the head and substrate in order to deposit the droplet on the target location of the substrate. Moreover, the printed substrate needs to be unloaded, and a new substrate should be loaded for printing, especially for printed electronics applications. A camera can be used to view the substrate to identify the printing position in the substrate in order to align the substrate with respect to motion stage axes prior to printing. This may take a considerable amount of time, and jetting should not occur during preparation for printing. During the non-jetting period, the ink on the nozzle surface can dry, and consequently, the jetting behavior of the first few drops is likely to differ from that observed during steady-state jetting. The existence of this first-drop problem has been discussed in the literature [1-3], and if a significantly abnormal jetting behavior is present, the printing quality can be affected accordingly. As a result, a proper measurement method should be developed to evaluate the jetting failure.

In this study, a high-speed camera is used to measure the first-drop failure because this is an effective means to measure the transient droplet behavior. To the authors' knowledge, only a few articles have been published to address the measurement of first-drop dissimilarity, and Famili et al. were probably the first to discuss the measurement of first-drop dissimilarity using a high-speed camera [4]. In their work, a frame rate of 2800 fps (frame per second) was used to acquire one single image for each droplet that was generated with a jetting frequency of 2.8 kHz [11]. However, the use of the same frame rate as the jetting frequency may have drawbacks in that a delay in the starting trigger of the high-speed camera with respect to the jet signal should be optimal in order to capture the jetting image. Otherwise, the image is very likely to capture background only, missing the droplet in the image.

In this study, we mainly discuss the jetting speed in order to evaluate the first-drop behavior because this can be measured with improved accuracy [1]. The use of the jetting speed of the droplet is straightforward to evaluate the inkjet since it is related to the jettability and the accuracy of the droplet placement. In the previous work, the relative location of the droplet is used to understand the relative jetting speed, instead of the jetting speed [3], since the jetting speed could not be measured due to the use of only one image per drop. Note that at least two droplet images per drop should be acquired in order to measure the jetting speed [1]. As a result, we used a 9 kfps acquisition in this study to measure the first-drop dissimilarity of a droplet jetted with a jetting frequency of 1 kHz. Since the image frame rate is an integer multiple of the jetting frequency, the first drop can be easily evaluated by means of the repeatability of the droplet location in the acquired image. Also, by using a higher frame rate than the jetting frequency, drop imaging is less dependent on the starting time of image acquisition of the high-speed camera and at least two jetting images can be taken per droplet to calculate jetting speed.

Many factors could affect the behavior of the first drops. The most common causes for this are probably the changes in the jetting properties of the ink due to an increase in viscosity or surface tension, which are related to the evaporation of ink on the nozzle surface. Jet failures due to evaporation are closely related to the non-jetting idle time (pause time), so it is important to understand the effects of the non-jetting idle time on the first-drop failures. In this study, we propose the use of high-speed camera imaging techniques to evaluate the first-droplet dissimilarity in relation to non-jetting idle time. To the author's knowledge, few papers have discussed the effect of the non-jetting time on first-drop jet failures. The characterization of effect that the non-jetting idle time has on the first drops can be useful to develop a jet failure prevention scheme.

Measurement methods for first drop

For experiment, a single nozzle head (MJ-AT, Microfab, USA) with a nozzle diameter of 50 μm is used for the printhead.

Silver ink from ANP (Silverjet, DGP-40TE-20C, ANP, South Korea) was used as a jetting material in order to investigate the effects of the non-jetting idle time. The ink has an Ag particle content of 30 wt.%, and the main solvent is TGME (Triethylene Glycol Monoethyl Ether, $C_8H_{18}O_4$). The viscosity of the ink is 7.8 cP at 25° C.

To obtain proper jetting, a trapezoidal driving waveform is used for jetting [1]. The rising/falling and dwell times of the waveform were set to 6 μsec and 20 μsec, respectively. The amplitude of the driving waveform was adjusted to obtain the target jetting speed. To simplify the analysis, a low jetting speed of 2 to 3m/s was used since a low jetting speed produces fewer satellite droplets. Also, image blur due to droplet movement can be reduced by using a low jetting speed. Nevertheless, this method can be extended to higher jetting speeds without a loss of generality.

The same digital trigger signal is used for both the high-speed camera and the jetting driver in order to understand and measure the jetting images for the first few drops by simultaneously starting the image acquisition and jetting. We used the steps described below to investigate the effect of non-jetting idle time, as shown in Fig. 1.

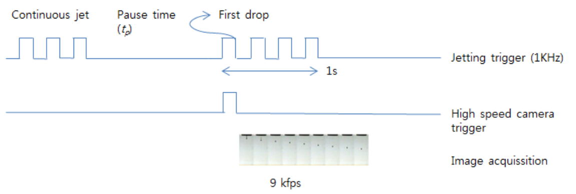

__Figure 1__. Measurement schemes for the first-drop behavior with respect to the pause time.

1) Continuous jetting with sufficient time to ensure steady-state jetting.

2) Jetting is stopped for a pre-determined non-jetting idle time, tp. During the non-jetting period, both the high-speed camera and the jetting driver wait for the trigger to start jetting and for image acquisition.

3) After the pre-determined pause time, the jetting and image acquisition will start simultaneously to measure the first-drop behavior.

The starting trigger after the pause time has been generated using digital I/O from a multi-function data acquisition I/O board (PCI-6221, NI, USA). The digital trigger can be used to start the digital pulse train from a counter in the PCI-6221 using a pre-determined frequency for ink jetting. Here, a jetting frequency of 1 kHz was used. At the same time as the starting trigger for jetting, the image acquisition is started with a frame rate of 9 kfps, which is 9 times higher than the jetting frequency. Note that the internal clocks for the jetting frequency and frame rate of the high-speed camera are independent in this experiment. As a result, there might be slight synchronization errors, even though we have used the same starting trigger for both devices. The magnitude of the synchronization errors and the effects on drop imaging will be discussed later.

It is important to set the frame rate to an integer multiple of the jetting frequency. As a result, the behavior of successive drops can be examined at the same time as jetting by inspecting every 9th frame. In particular, the first-drop behavior (transient drop behavior) can be evaluated by comparing the location of the droplet in every 9 images. If the behavior of the first few drops is different from the droplet image in steady-state jetting, then this could indicate that drying has occurred on the nozzle.

We used a high-speed camera (SpeedCam MiniVis, Weinberger, Switzerland) to capture the jetting images. The camera has an image resolution of 1280x1024 pixels at 500 fps, and the maximum recording speed is of up to 112,000 fps. Note that the image resolution has been reduced as the frame rate increases. For example, in the case where images are acquired at 9 kfps, the number of pixels in the acquired image is of 80x128, which is a very-low in resolution. The exposure time for the camera should be sufficiently short in order to avoid image blur due to droplet motion. However, a shorter exposure time results in dark images if the lighting is not sufficiently bright. In this study, we set the exposure time to 3 □s to take the lighting brightness into account. After the acquisition of 1000 images at a frame rate of 9 kfps, the images are downloaded from the high-speed camera to the PC for further analysis.

Experimental results

To investigate the first drop effects, 6 sets of jetting images are acquired by using a range of non-jetting pause times of t_p=0, 60, 180, 300, 420 and 540 sec.

For easier image analysis, the frame number of images, n=0,1,2,…999, in sequential order can be converted to drop number, d and time, t, from jetting signal as

d =Quotient (n/r) + 1,

t=Remainder (n/r)/frame rate≈Remainder (n/r)*0.11ms, (1)

where r is the integer 9, which corresponds to a camera frame rate divided by the jetting frequency.

By using equation (1), images can be effectively sorted with respect to the drop number d and time t from frame number n. The frame number is in the sequential order of the image acquisition. For example, the frame numbers for the starting time of each droplet, that is t=0 sec, can be sorted as n= 0,9,18…, which corresponds to drop numbers of d=1,2,3.., respectively.

For direct comparison, the jetting images of each first drop *d*=1 are compared, as shown in Fig. 1.

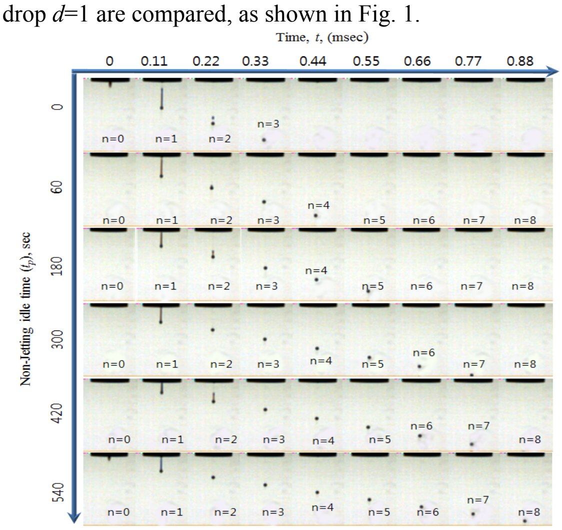

__Figure 2__. Effects of the non-jetting pause time on the first-drop behavior

Fig. 2 clearly shows that an increase in the pause time (vertical axis), t_p, results in a slower jetting speed than that at the steady state with t_p=0. Note that a droplet location closer to the nozzle indicates a low jetting speed, which is contrary to that observed in a previous publication [4] that presented experimental result of a faster jetting speed for the first drop when compared to that of steady-state jetting.

It is well known that it takes time for ink to extrude from the nozzle because the propagation of a pressure wave of ink is required inside of the inkjet head. In the case of a Microfab head, it normally takes more than about 40 μsec for ink extrusion due to the driving voltage length (about 30 μsec) and the ink pressure wave propagation time. As a result, we cannot observe droplet extrusion at the time of jetting triggering at *t*=0. Nevertheless, we observed a slight droplet extrusion for t_p=0 sec and 540 sec at *t*=0, i.e. *n*=0, which indicates that the starting time of the image acquisition may have a slight delay of up to 50 μs with respect to the jetting trigger. This is related to synchronization errors because two different internal clocks are used to start both the jetting and imaging acquisition. Nevertheless, the magnitude of the error is acceptable to conduct an analysis of the first drop behavior.

As shown in Fig. 2, the droplet location in the image for an idle time of t_p=60 sec was not significantly different from that of the steady state t_p=0. As a result, the placement error from the first droplet may be negligible in the case of t_p = 60 sec. We also observed that first-droplet jetting was possible even if the pause time had increased up to t_p=540 sec, which is acceptable for most printing applications. However, the jetting speed was very slow with t_d=540 sec when compared to that of the steady state case. This slow jetting speed is likely to be alleviated after a few drops of jetting, and the number of droplets required to recover the jetting status may differ according to the ink used and other jetting conditions. To provide a better understanding, we take the example of the jetting images for a pause time of t_p= 540 sec. For this purpose, the jetting images are sorted according to the drop number (horizontal axis) d and time (vertical axis) t, as shown in Fig. 8. The sorting method based on the sequential frame images, n, is discussed in Equation (1).

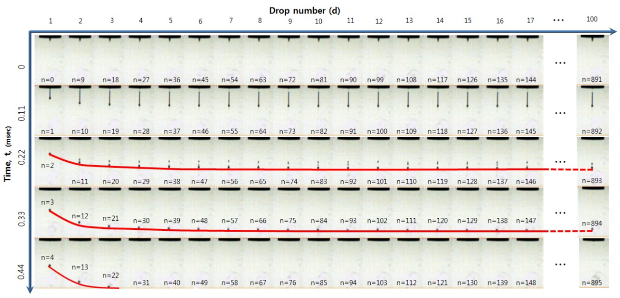

Figure 3. Jetting image plot of tp=540 sec with respect to the drop number d and time t.

Fig. 3 shows that for the first drop d=1, the drop locations (first column) are significantly different from those of other drops (other columns, d=2,3,4..). It is clear in the jetting images that jetting recovered quickly within 2-3 drops, and the bottom-of-droplet locations are overlaid using a red line to conduct a comparison of the droplet locations for each droplet. In this manner, we can easily judge the jetting status by the straightness of the overlaid line. If the locations of the droplets do not change (straight line), then we can assume that jetting has achieved steady-state status. As shown in the figure, only a few drops prior to actual printing are required to produce steady-state jetting, even when the non-jetting idle time is as long as 540 sec.

Alternatively the jetting speed plot with respect to drop number n and pause time t_p can be used to evaluate the jettability after various trial pause times as shown in Fig.4.

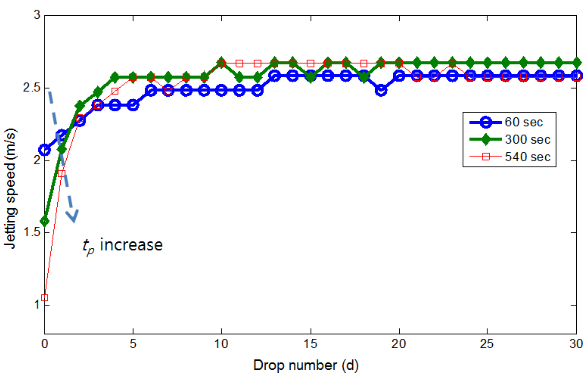

Figure 4. Jetting speed plot of the ANP silver ink with respect to drop number and non-jetting idle time

As shown in Fig. 4, only a few drops are required to reach 80% of the steady-state jetting for all t_p= 60, 300 and 540 sec. Note that the number of droplets required for steady-state jetting may not be directly proportional to the non-jetting idle time, as shown in Fig. 4. The use of the jetting speed graph with respect to the drop number has advantages over sorted jetting images in that it is easier to conduct direct comparisons of many different conditions. However, it should be noted that the jetting speed is difficult to calculate when many droplets are present on the image, such as with a droplet image containing many satellites or a high-frequency jetting image [5].

Conclusions

The first-drop dissimilarity is evaluated using a proposed method based on high-speed camera imaging. To effectively understand the jetting behavior, we set the frame rate of the high-speed camera to 9 kfps, which is an integer multiple of the jetting frequency of 1kHz. In this manner, the effect of the first-drop can be effectively understood by conducting a comparison of droplet images sorted according to drop number and time because the droplets viewed once every 9 images will have occurred at the same time from jetting. This method is not limited to a specific jetting frequency and camera frame rate since the proposed method can be extended for use in any cases where the image frame rate is an integer multiple of the jetting frequency.

We have observed that the jetting speed of the first drop slowed down as the non-jetting pause time increased, which is contrary to what was previously found by another group. The inkjet head was shown to develop non-jetting conditions as the non-jetting period is increased with the jetting speed tending toward zero. To minimize the degree of the first-drop dissimilarity after a given non-jetting idle time, we propose the use of a required number of jetting driving voltage pulses to recover the jetting status. This can be achieved simply through pre-spitting prior to printing, and the number of drops required for jetting status recovery can be jetted on a dummy area prior to printing to ensure better printing quality.

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Author Biography

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