Tracking based inkjet measurement for evaluating high frequency ink jetting

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Abstract

Inkjet technology has been used as a manufacturing tool for printed electronics. To increase productivity, the jetting frequency needs to be increased. When using high frequency jetting, the printed pattern quality can be non-uniform since jetting performance, including jetting speed and droplet volume, can vary significantly according to the jet frequency increase. Therefore, high frequency jetting behavior must be evaluated properly for performance improvement. However, it is difficult to measure high frequency jetting behavior using the previous vision analysis methods because subsequent droplets are very close and can even merge. In this paper, we present vision measurement techniques to evaluate the drop formation of high frequency jetting. The proposed method is based on the tracking of target droplets, and other subsequent droplets can therefore be excluded in the image analysis by focusing on the target droplet.

Introduction

The application of inkjet technology has expanded from home printers to manufacturing tools. To use the piezo inkjet as a manufacturing tool for printed electronics, the productivity and reliability of the technology have become the two key issues. To increase the productivity, high frequency jetting is required. In the case of high frequency jetting, subsequent droplets can be ejected before the pressure wave from the previous drop has sufficiently decayed inside the inkjet head; this will affect the jetting behavior [1]. To ensure printing uniformity, high frequency jetting behavior must be evaluated prior to any improvement. Recently, the use of a pressure wave signal measured by piezo self-sensing was proposed to evaluate the waveform for high frequency jetting performance [1]. However, jetting speed and droplet volume behavior are difficult to understand since the amplitude of the self-sensing signal may not be directly related to jetting behavior. Therefore, in this study, vision analysis methods are mainly discussed because the high frequency effect on printing quality can be easily understood by visual means.

For inkjet vision analysis, images from charge-coupled device (CCD) cameras are widely used to measure droplet jetting speed as well as droplet volume [2,3]. By using light emitting diode (LED) lights synchronized to the firing signal, droplet images appear to be frozen in the acquired CCD camera image. Image processing techniques are then used to measure jetting speed and droplet volume [2-4]. However, the jetting speed varies significantly during drop formation. As a result, the measured jetting speed using the previous methods in [3,4] can differ according to the selection of the two timings or measurement location. Recently, a so-called instantaneous jetting speed curve was proposed to overcome the shortcomings of jetting speed measurement based on two timings [5]. The instantaneous jetting speed curve assists in understanding the jetting speed variation during drop formation. Also, the relative jetting speed of satellites with respect to the main droplet can be measured during drop formation. However, measuring high frequency jetting behavior may have limitations because the image analysis might be very complicated due to the many subsequent droplets on the acquired images. Furthermore, the measurement of drop formation is even more difficult since the subsequent droplets might merge with the main droplet of interest. To the best of the authors' knowledge, no standardized methods have been developed and few studies have discussed vision measurement techniques to evaluate the jetting performance of such complex high frequency jetting behavior. Inkjet industries seem to have their own techniques to measure such high frequency jetting behavior, and the measured results are likely to differ according to their own measurement methods.

In this study, to measure high frequency jetting behavior effectively, we propose a measurement method based on tracking of the main droplet Also, the use of the so-called variable region of interest (ROI), of which the size and location is re-defined in each sequential image, is proposed to focus the image analysis on the tracked target droplets, excluding the image analysis of the other subsequent droplets.

Vision measurement technique and image analysis

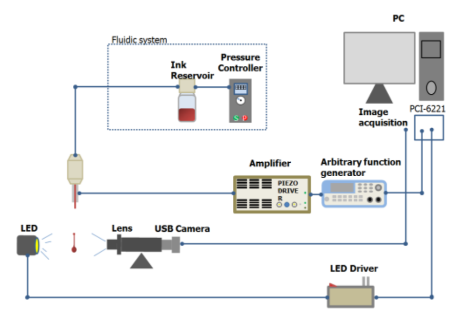


Figure 1. Schematic of inkjet measurement system.

A single nozzle head (MJ-AT, Microfab, USA) was used as the jetting device. The nozzle diameter of the printhead used for the experiment was 50μm. Here, Standard inkjet ink (XL-30, Dimatix, USA) was used as a jetting fluid. To visualize the jetting image, a CCD camera (STC-TC202USB, Sentech, Japan) was used for jet image acquisition. An adjustable zoom lens (ML-Z07545, MORITEX, Japan) and a lens adaptor (ML-Z20, MORITEX, Japan) were used to acquire magnified images of the inkjet behavior. To obtain a frozen jetting image, 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. The details of the experimental setup shown in Fig.1 can be referenced in [5].

To illustrate frequency effects on jetting, the jetting images of different frequencies ranging from 1.5kHz to 20 kHz are shown in Fig. 2. The same trigger delay of 70 us for the LED light with respect to the jetting trigger signal was used so that the jetting image can be compared at the same time. As seen in Fig. 2, the droplet jetting behavior varies significantly according to jetting frequency.

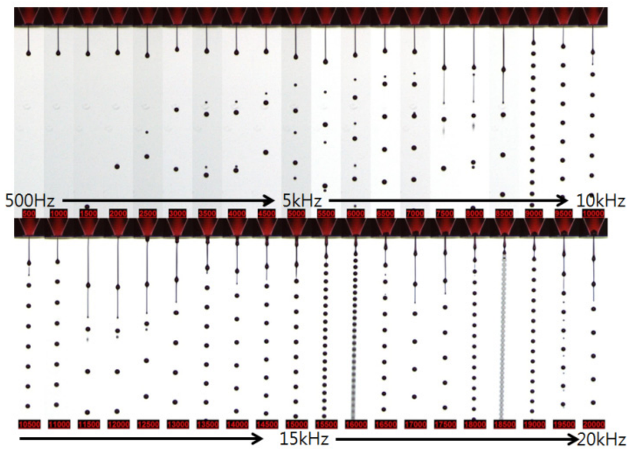


Figure 2. *Jetting frequency effects at 70 μs.*

In the case of low frequency such as 1kHz, the jetted droplet of interest can easily be separated from other subsequent droplets for droplet vision analysis. However, in the case of 7.5 kHz or higher jetting frequency, the jetting behavior from a pulse voltage was difficult to analyze by using conventional binary image analysis due to the large number of subsequent droplets in the acquired images.

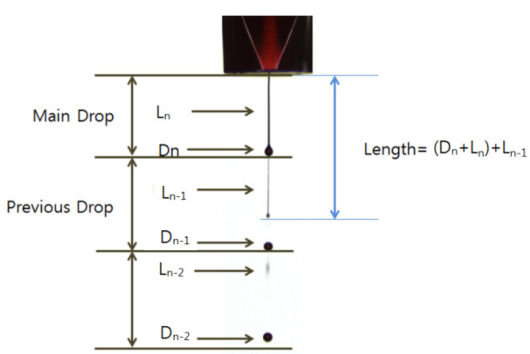
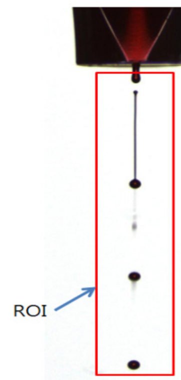


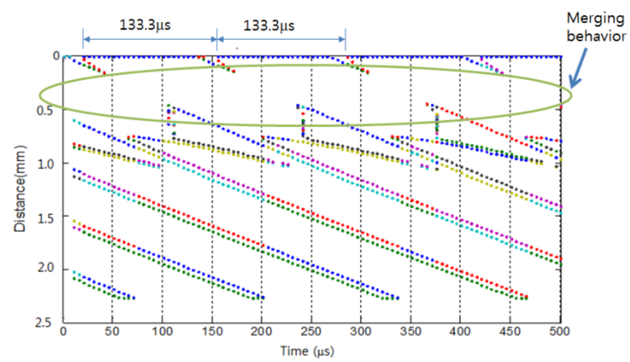
Figure 3. *High frequency jetting behavior (7.5 kHz) at 70μs.*

For better understanding of high frequency measurement issues, the jetting behavior of 7.5 kHz will be discussed in detail without loss of generality. The main droplet of interest was indicated as D_n as shown in Fig. 5. Here, the subscript n refers to the current droplet number and previous and subsequent droplets can be denoted as n-1 and n+1, respectively.

It is interesting to note that in the case of 7.5 kHz, two different ligaments from previous droplets denoted as Ln-1, and the current droplet ligament denoted as Ln, are attached to the main droplet (D_n) of interest. As a result, the merged droplets (L_{n-1}, D_n, L_n) are likely to be treated as one droplet with a long ligament when using the binary analysis described in [5]. Note that in the case of a low frequency jetting of less than 5 kHz, the ligament L_{n-1} from the previous jetting barely merged with the current droplet, D_n.



(a) Fixed ROI



(b) Drop formation curve with fixed ROI

Figure 4. *Drop formation measurement using fixed ROI (7.5 kHz jetting)*

For better understanding, the fixed ROI shown in Fig. 4(a) was used to obtain the drop formation curve of 7.5 kHz inkjet jetting. Since the jet behavior is repeated with intervals of 133.3us (1/7.5 kHz), a large number of drop formation curves for each subsequent droplet are obtained, as shown in Fig. 4(b). Jetting behaviors including droplet location, ligament behavior, and droplet volume per single jetting trigger are difficult to understand from the drop formation based on fixed ROI due to close subsequent droplets. Furthermore, the jetting behavior near the nozzle (0-0.5mm) shows heavily merged behavior, making the analysis seemingly impossible.

Variable ROI

To overcome previous limitations, a so-called variable ROI technique is proposed. The lower and upper locations of the ROI were re-defined in each sequential image to focus on the tracked target, excluding other droplet for droplet analysis.

Basically, two tracked subsequent droplets were used to define the boundary of ROI. However, in the initial stages, only a single droplet, or even no droplet, was tracked. As a result, we need to consider the number of tracked droplets to define the variable ROI. This is a generalized method and can be applied to a broad range of frequencies since it can also be used for low frequency jetting measurement.

1) Stage 1: No tracked droplet

In the initial stage, the droplet of interest may not appear in the acquired image because it will take some time for the pressure wave of ink inside the inkjet head to propagate before the ink is ejected from the nozzle. In the case where no droplets are detected, image analysis will be omitted and the initial extruded target droplet will be searched from the next sequential image.

2) Stage 2: Single tracked droplet

When the initial extruded droplet of interest is detected by using the edge detection described in Fig. 5, the droplet location is tracked via a tracking algorithm in each sequential image. From the tracked droplet, the size and location of ROI are re-defined such that the lower location of ROI can be defined by the bottom location of the tracked droplet, while the upper limit is fixed at the nozzle surface as seen in Figs. 6(a) and 6(b). This process continues until the subsequent main droplet appears from the acquired image.

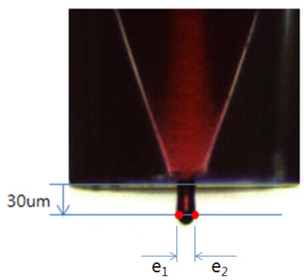


Figure 5. *Edge detection for tracking of initial drop formation*

3) Stage 3: Two tracked droplets

The subsequent droplet will appear from the nozzle after the jetting period (inverse of jetting frequency) from the initial extruded droplet detection. The initial subsequent droplet can also be detected by the same edge detection algorithm described earlier. The two consecutive main droplets were then tracked simultaneously to define the variable ROI.

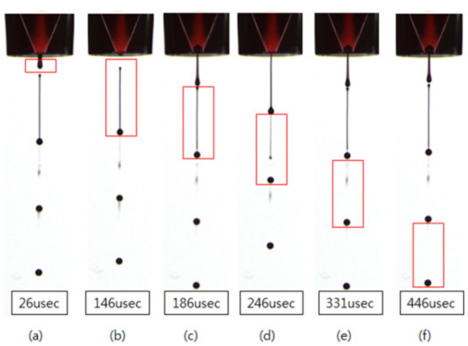


Figure 6. *Variable ROI based on tracking of jetting droplet of 7.5 kHz.*

From two subsequent droplets, the lower and upper boundaries of the variable ROI can be defined by the bottom locations of the two tracked droplets as seen in Figs. 6(c) to 6(f).

Drop formation curve

By using the proposed variable ROI, the droplet of interest can be effectively analyzed, excluding the image analysis of many of the other subsequent droplets.

Fig. 7 shows the measured drop formation curve of the 7.5 kHz jetting by using a variable ROI. The details for obtaining a drop formation curve can be found in [5]. Compared to the drop formation measurement using fixed ROI shown in Fig. 4(b), the jetting behavior of high frequency jetting can be clearly understood if the variable ROI is used. However, it should be noted that the droplet of interest could interact with subsequent droplets in the case of high frequency jetting. As a result, the droplet volume as well as the jetting speed could be affected by the merging behavior. In the initial stage, the initial jetted droplet could interact with the ligament of the previous droplet at the bottom boundary of the ROI (0-110 μs). Later, the long ligament in contact with the upper limit of the ROI interacts with the subsequent droplets (130-250 μs). For better understanding, Figs. 6(c) and 6(d) show images at 186 and 246 us, respectively, when the long ligament contacts the upper limit of the ROI. These interactions are dominant in the beginning and become less significant during drop formation.

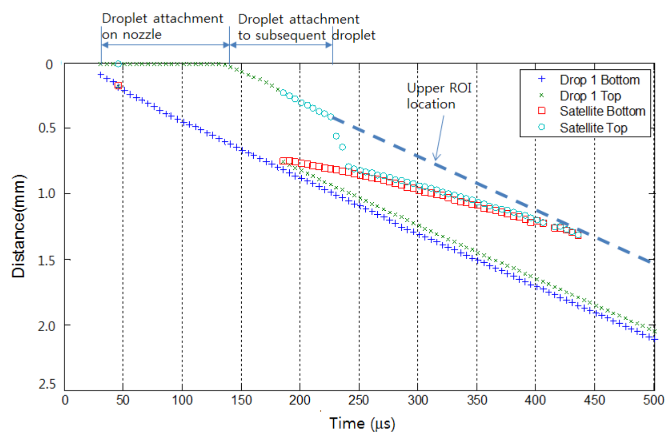


Figure 7. *Drop formation curve of high frequency jetting (7.5 kHz)*

Jetting speed curve

No standardized method for jetting speed measurement seems to have been established, and the measured results might differ according to the measurement location. The measurement method needs to be generalized and includes the case of a droplet with a ligament and satellite because the jetted inkjet droplet is likely to have a long ligament and satellite in most cases.

On the other hand, the jetting speed of the main droplet and satellite with respect to time can be calculated from the drop formation curve [5]. However, if the previous fixed ROI in [5] is used, the jetting speed curve will be very complex due to many other droplets in the case of high frequency jetting. Therefore, the jetting speed curve based on variable ROI is effective to understand the jetting behavior of high frequency jetting as seen in Fig. 8. Fig. 8 shows that jetting speed can vary during the drop formation due to the viscoelastic behavior of the ligament [5]. Additionally, in the case of high frequency jetting, the interaction with subsequent droplets may influence the jetting speed.

In the case of 7.5 kHz jetting shown in Fig. 8, the main droplet jetting speed (4~6m/s) was higher than the satellite jetting speed (1~2.5m/s). Therefore, the satellite with a long ligament eventually merged with the subsequent droplets at 420µs.

Note that the measurement of the jetting speed curve is more sensitive to image resolution and image quality. Especially, the satellite is affected more by such errors because the smaller and thinner images are subject to image noise. In this study, the camera resolution of 1600x1200 is used for measurement and the zoom lens is adjusted such that the pixel resolution can be about 2.14 µm per pixel in our measurement system. If a high magnification lens is used, then only the local behavior along the short travel distance is measured. Therefore, the higher resolution camera is recommended if the measurement quality needs to be increased.

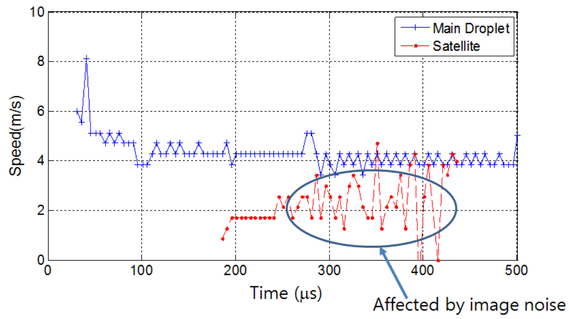
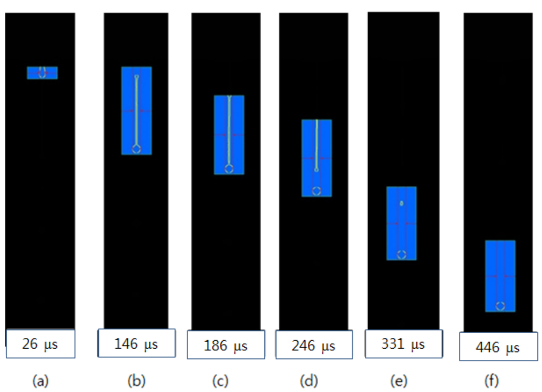
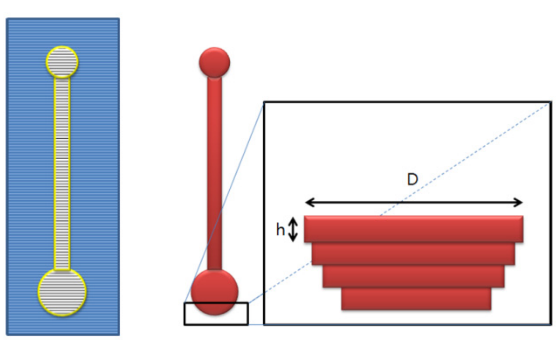


Figure 8. *Instantaneous jetting speed curve of 7.5 kHz jetting*



(a) Droplet volume measurement with respect to time (7.5 kHz)



(b) Droplet volume calculation algorithm

Figure 9. *Image processing algorithm for droplet volume measurement*

Droplet volume measurement

One of the main advantages of the variable ROI is that the droplet volume behavior of the target droplet can be calculated while excluding many other subsequent droplets in the image, as shown in Fig. 9. Here, an edge detection algorithm is used to measure the droplet volume. To define a set of horizontal ROI lines, the variable ROI is equally divided in the vertical direction. Then, from each ROI line, the edges are detected to calculate the droplet volume. Note that the diameter of each cylinder can be calculated by using the detected edge information and the droplet volume is the summation of the sliced cylinder volume as seen in Fig. 9(b). A similar method used to calculate the droplet volume has been discussed in previous reports [2,9]. However, the previous method did not take account of the droplet measurement of high frequency jetting and it cannot be directly used in the case of close or even merged droplets.

Fig. 10 shows the drop volume behavior of 7.5 kHz jetting measured using the variable ROI. The interactions among subsequent droplets can be understood from the measured volume with respect to time. The measured volume changes continuously until the droplets are totally detached from the nozzle and the interaction with the subsequent droplets diminishes. As a result, the measured volume can differ according to the measurement time and location, and measurement standardization is thus needed. From the droplet volume behavior with respect to time, we can judge the proper measurement location from the droplet volume, where the exact droplet volume per single jetting trigger can be measured.

1) Beginning stage (0-150 µs)

In the beginning, the droplet volume increases until 150 µs because the droplet is being developed from the nozzle with an increased ROI size. In addition, in this particular case, the ligaments of previous droplets may be attached to the droplet of interest in the initial stage. The ligament or satellite of the previous droplet is slower than the main droplet in the case of 7.5 kHz. As a result, the ligament (or satellite) will merge with the main droplet of interest, resulting in an additional droplet volume increase in the beginning stage.

2) Interaction with subsequent droplet (150-240 µs)

The subsequent droplet may appear after 133 µs from extrusion of the droplet of interest in the case of 7.5 kHz. Even in such case, the ligament of the current droplet may not be pinched off from the nozzle. Due to the slower speed of the upper ligament, the droplet volume of interest decreases from 130 pL to 110 pL because a portion of the ligament is lost by adding the droplet volume to the subsequent droplet.

3) Droplet volume measurement time (240 µs -)

Finally, most of the slow ligament merges with the subsequent droplets at the time of 240 us, when the droplet volume does not change significantly. From Fig. 7, we can determine the corresponding location from the nozzle surface to be about 1.5 mm. The measured droplet volume per single trigger is about 110pL. In this way, the droplet volume per single trigger can be measured in the case of high frequency jetting.

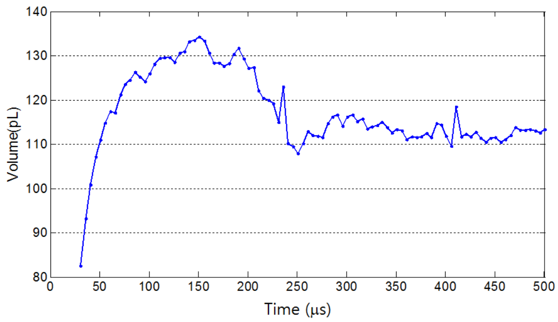


Figure 10. *Droplet volume behavior during drop formation*

Conclusions

To overcome such difficulties in measuring high frequency jetting, we propose a new image analysis algorithm that can focus on a droplet of interest excluding other subsequent droplets. The measurement algorithm consists of three steps: 1) tracking algorithm for a target droplet; 2) defining variable ROI based on the tracked target droplets at each sequential image; and 3) Drop formation analysis and droplet volume measurement based on the variable ROI.

By using the variable ROI, the droplet volume with respect to time was shown to be effective in evaluating the interactions among subsequent droplets due to the close droplet locations.

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Author Biography

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