

Impact on Droplet Placement on Paper by the Level of Droplet Flight Stability in a Continuous Ink Jet Printer

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Abstract

This report presents a study of how the level of droplet flight stability influences the positioning of droplets on paper for a continuous ink jet printer based on the Hertz technique. The droplet flight stability was measured with the aid of an optical system that provides a measure of stability based on the standard deviation for time between droplets for a large number of droplet-to-droplet intervals. The accuracy of droplet positioning on paper was analyzed by identifying dots in a grabbed image of a print and measuring the distance between them. The study shows a strong connection between low stimulation voltage, low droplet flight stability, and low precision in droplet placement on paper. The droplet flight stability was measured at a distance of 7 mm from the nozzle. When the standard deviation for droplet-to-droplet distances in flight was below 15° of the 360° droplet formation period, the standard deviation for distances between dots on paper was below 10 µm. No errors concerning the amount of ink in a pixel were present at this level of stability, which was reached for stimulation voltages above 4 V peak-to-peak (Vpp).

Introduction

The Hertz continuous ink jet printer[1] creates images by positioning an arbitrary number of ink droplets in each of the pixels on paper (Fig. 1). This technique is based on charging and deflection of individual droplets from a conductive continuous ink jet. To gain complete control of the droplet placement on the paper it is essential that the droplet formation is stable and that the electrical control signals are synchronized to the droplet formation.

A cylindrical liquid jet spontaneously breaks up into droplets due to disturbances on the surface of the jet.[2–4] The naturally introduced disturbances grow exponentially until their amplitude equals the radius of the jet, that results in break up of the jet (cf. Fig. 2). The disturbances are, however, random to their nature and will not produce droplets at a constant rate. To make the creation of droplets repeatable a piezoelectric crystal is glued to the nozzle and periodic vibrations from the electrically stimulated crystal perturb the jet. This will result in a stabilized droplet formation at a rate determined by the stimulation frequency within the region where stimulated droplet formation is possible.

The actual velocity for each individual droplet is dependant on processes at the breakup and small variations in droplet velocity can be found even though the jet is perturbed with a stimulation signal with a constant oscillating period.[5,6] By increasing the amplitude of the stimulation signal the droplet-to-droplet velocity variations are reduced and the droplet flight stability is improved.[7]

The charging voltage and the deflection field strength are chosen to provide a deflection of about 0.5 mm at the knife edge. It is essential that the droplets to be printed are fully discharged and that the droplets to be removed have enough charge to safely be caught by the knife edge. The correct charge of the droplets is established if the conductivity of the ink is sufficiently high and the switching of the charging voltage is synchronized to the droplet formation. The switching of the voltage should ideally occur just after a

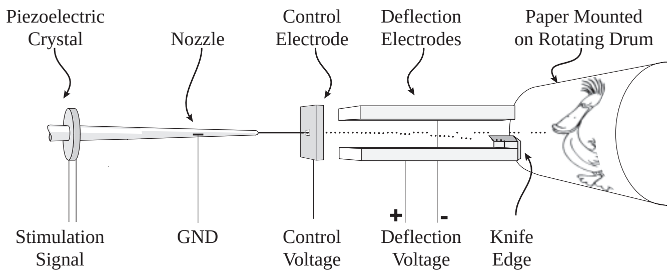

Figure 1. The Hertz continuous ink jet printer principle. A positive control voltage pulse with variable duration applied to the control electrode synchronized to the droplet formation process will cause charging of unwanted droplets. The charged droplets will be deflected downward and caught by the knife edge due to the high-voltage field between the deflection electrodes. The uncharged droplets will pass the deflection field unaffected and hit the paper in the desired pixel.

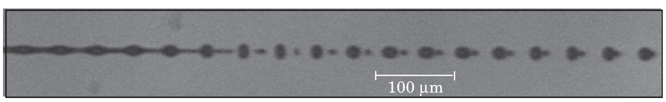

Figure 2. A liquid jet (ϕ = 10 µm) at the point of droplet formation viewed in stroboscopic light. The nozzle is stimulated with 1 MHz. The ligament between the drops releases at both ends and forms a satellite droplet that merges backward after approximately 15 droplet diameters.

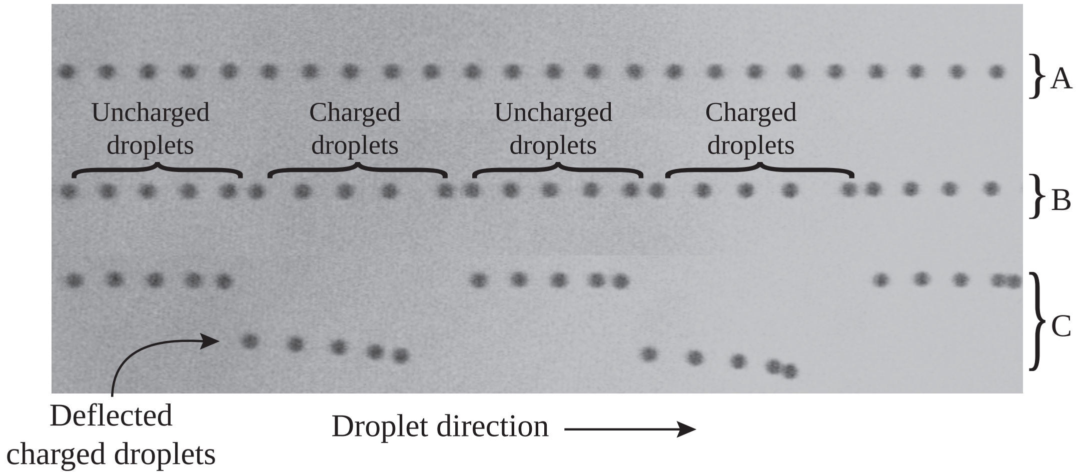

Figure 3. The effect of Coulomb repulsion on droplets in flight. The three images (A, B ,C) show droplets at 10 mm distance from the orifice. Sequence A shows uncharged droplets. Sequence B shows groups of five uncharged and five charged droplets without any deflection field. Sequence C shows the same groups as sequence B but with the presence of a deflection field which forces the charged droplets downwards. The stimulation frequency is 1 MHz and droplets travel to the right with a velocity of approximately 60 m/s.

droplet has detached from the jet. The following droplet is then connected to the rest of the jet with a relatively large ink filament, resulting in a fairly low resistance. The resistance will increase as the filament becomes thinner during the droplet formation process. Toward the end of the droplet formation cycle the resistance through the ink is too high to allow complete charging or discharging of a droplet. Normally, for a 10-µm jet at 1 MHz droplet formation frequency, the droplets are fully charged or discharged if the control voltage is switched during the first third of the droplet formation period.[8–10]

Further, is it important to prevent merging of charged and uncharged droplets in flight.[11–14] The merging is caused by Coulomb repulsion between charged droplets and is further accentuated by unstable droplet flight. The result is a droplet with the same charge as a single droplet but with twice the mass. Consequently, the deflection will be decreased, resulting in too much or too little ink on the paper, depending on whether or not the droplet will pass the knife edge. To minimize the problem the charging voltage should be as low as possible and the nozzle should be operated at high droplet flight stability. It is favorable to let the droplets enter the deflection field shortly after jet cutoff so the charged and uncharged droplets are separated before the merging occurs.

The repulsion of charged droplets is exemplified in Fig. 3 where track B is recorded without deflection field. We can see how the first and last droplets in the charged groups are forced toward the uncharged groups. Track C demonstrates how aerodynamic forces “cancels” the repulsion when the droplets are separated by the deflection field. Figure 3 is recorded at a distance of 10 mm from the nozzle. At a distance of 7 mm from the nozzle, the deflection of charged droplets is one droplet diameter, which is required to prevent merging. This means that the sum of Coulomb repulsion and instability in droplet flight must not result in droplet merging before the droplets reach this distance.

In the following, measurements are presented on how varying droplet flight stability in a nozzle system will affect the accuracy in droplet placement on the print substrate. The droplet flight stability of the nozzle system is characterized using an optical method we presented previously.[7]

Materials and Methods

We studied the performance of an in-house built continuous ink jet printer using a glass nozzle (Siemens-Elema, Solna, Sweden) with an orifice diameter of 10 µm, fitted with piezoelectric crystals by the manufacturer. The nozzle was mounted in a Perspex fixture, incorporating the control electrode during both the droplet flight stability study and the droplet placement study. In the printer, the nozzle and fixture unit are placed in a printhead that holds the deflection electrodes. Cyan ink (Siemens-Elema AB, Solna, Sweden) was used in all experiments. The viscosity at 25°C was 1.7×10^{-3} Ns/m^2 and the conductivity was 15 mS/cm. The change in surface tension and viscosity for a glycerol/water mixture similar to the ink is around –0.2 percent/degree and –2 percent/degree, respectively, at 25°C.[15]

An in-house developed piston pump was used to produce the ink driving pressure of 4.5-MPa. At this pressure, the jet emanated from the nozzle at a velocity of 56 m/s and the ink flow was 0.25 mL/min. The same pump and hoses were used throughout all experiments.

The control electronics is designed to enable synchronization between the droplet formation and the switching of the charging voltage in 32 steps over the 360° droplet formation period.

Droplet Flight Stability Measurements. The optical measurement setup used to study the droplet flight stability is shown in Fig. 4. A continuous HeNe laser beam illuminated the ink droplets and created a shadow image. This image was magnified by a microscope so that the focused image of one droplet entirely covered the light-sensitive area of a *p-i-n*-photodiode-based photodetector. The output from the photodetector was digitized by an oscilloscope and transferred to a computer for further analysis.

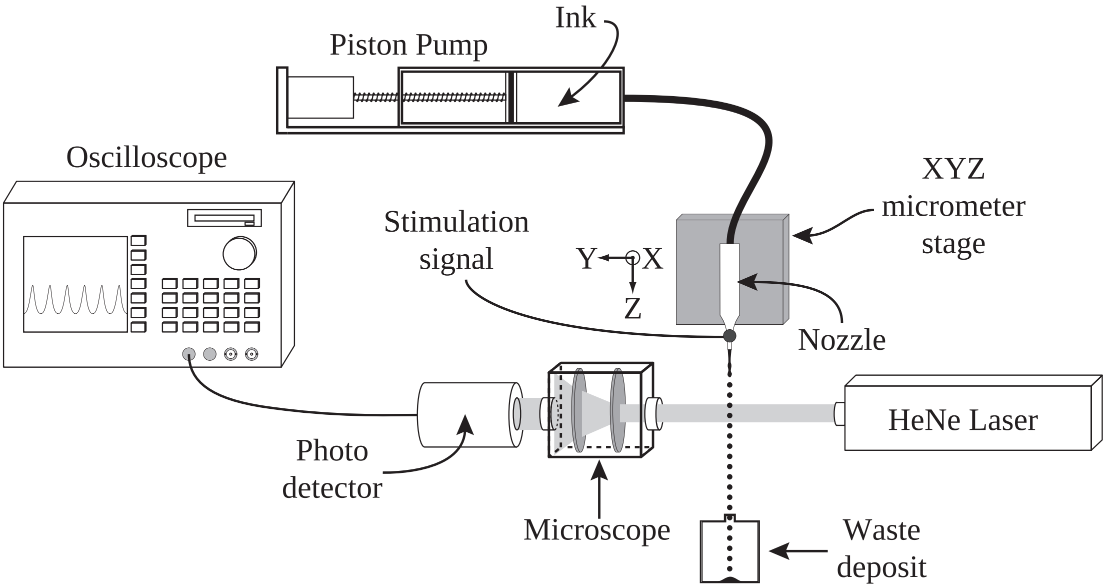

Figure 4. The optical droplet flight stability measurement setup.

The time between droplets was measured for a large number of droplets and the standard deviation for these data was used as a measure of flight stability. The oscilloscope has a memory depth, that enables the capturing of 100 consecutive droplets with a sampling rate of 200 mega samples/s and this procedure was repeated five times for each point of measurement. The standard deviation for the time between the droplets was transformed to degrees where a standard deviation equal to the period of the stimulation frequency corresponds to 360°.

To find a stable droplet formation frequency to use in the experiments the droplet flight stability of the nozzle system was first characterized between 800 and 1200 kHz. The stimulation voltage was kept constant at a level of 10 Vpp. The frequency range was selected based on the fact that the nozzle is designed to be operated around 1.0 MHz. After selecting a frequency to use, the droplet flight stability was measured at distances from 3 to 18 mm from the nozzle to select a suitable distance for the following measurements. Different droplet flight stabilities were then generated by varying the amplitude of the stimulation voltage. The droplet flight stability was characterized at stimulation voltages between 1.0 and 11.0 Vpp in the steps 1.0, 1.5, 2.0, 3.0, 4.0, . . . , 11.0 Vpp.

Droplet Placement Analysis. To study the effect of droplet flight stability on the positioning of droplets on paper, images were printed consisting of three areas containing 1, 2, and 3 droplets/pixel, respectively. Each area contained 100×800 pixels with the 100 pixels printed in the direction of rotation for the printer. The nearest neighbors to each pixel containing droplets were left empty to detect misplaced droplets. The images were all printed on high gloss paper (IRIS Graphics Inc., Bedford, MA) at a spatial resolution of 10 pixels/mm. Due to the empty pixels the distance between dots in the printouts were 200 µm.

The synchronization of the control signal to the stimulation signal was changed five steps, corresponding to a total of 56.25°, six times during each print due to the lack of automatic phase adjustment in our laboratory printer. This procedure ascertains that printing takes place with correct synchronization between the control voltage and droplet formation during some part of the print. After this empirical investigation the synchronization was adjusted and a new image was printed with the control voltage applied in the correct position within the droplet formation cycle. This procedure was performed for each level of stimulation voltage from the droplet flight stability characterization.

A microscope (SMZ-2T, Nikon, Japan) fitted with a gray-scale CCD camera (C5405, Hamamatsu, Japan) was used to capture a magnified part of the printout containing 96 printed dots (12 columns containing 8 dots) of the second printout. The video image (756×485 CCD pixels, 1/2 in. chip) was digitized with the aid of an image grabber (ImageGrabber, Neotech, US) mounted in a computer (Macintosh II fx, Apple, US). In the grabbed images, the gray-level of 255 corresponds to white and 0 (zero) corresponds to black. The level of magnification selected by the microscope is a trade-off between pixel resolution and number of printed dots in the image. The magnification of the image projected on the CCD chip was measured using a calibrated micrometer scale and was found to be 2.6 times giving that each pixel in the digitised image corresponds to 3.2×3.2 µm in the printout.

The grabbed images were analyzed using MATLAB (The Math Works, Natic, MA) running on a Macintosh 8100/110. The 12 columns in the grabbed image matrix (one for each printed column of dots) to be used for calculations were selected manually by searching for a minimum gray-level that matches the center of the dots. Once the columns were chosen the printed dots were automatically identified in MATLAB by the change in gray-level from the back-ground white to black back to white again (Fig. 5). Dots were selected as the parts of the print where the gray-level was less than 150. A polynomial of degree 4 was fitted to the sampled values of each dot and the fitted polynomial was derived to find the minimum of the polynomial. The root of the derived polynomial was used as an approx-

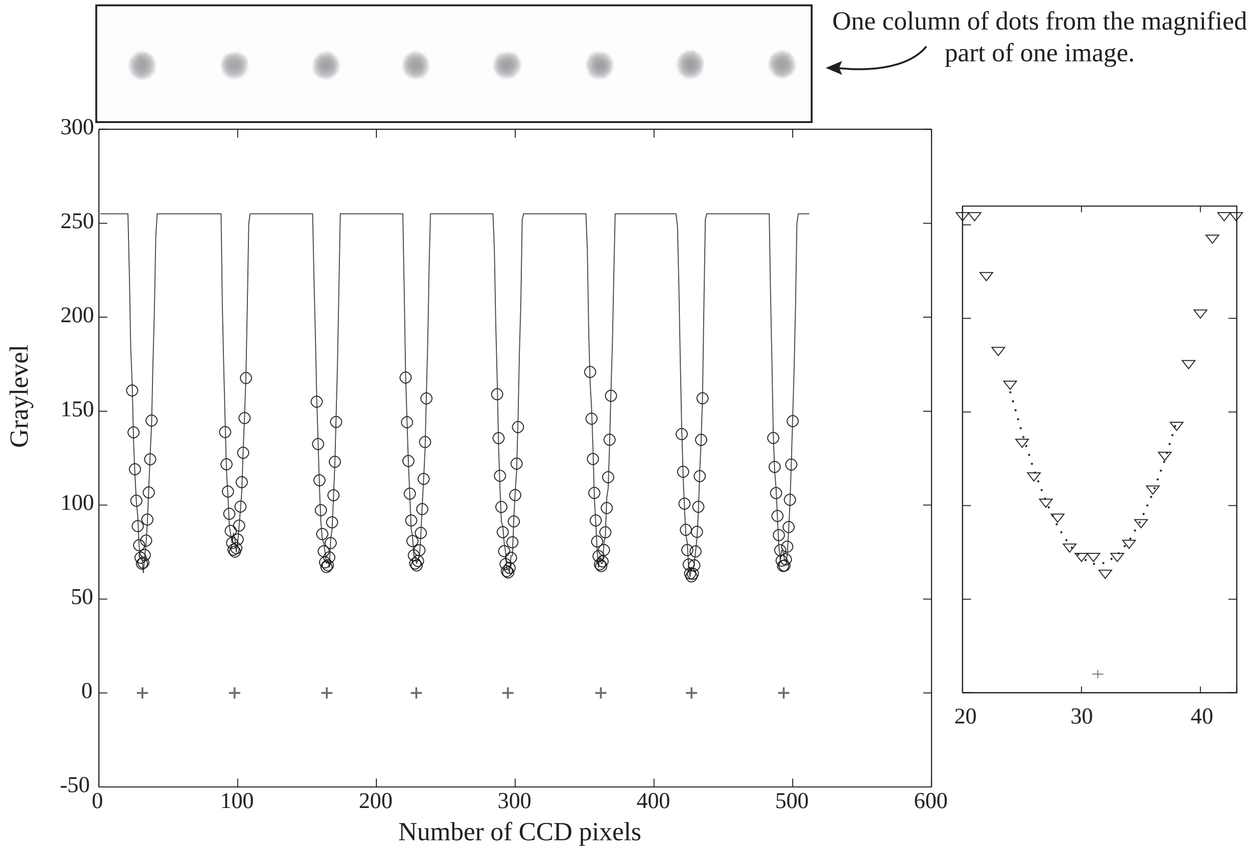

Figure 5. The grabbed image at the top of the figure is taken from a print out with 2 droplets per pixel printed with a stimulation voltage of 10 Vpp. The line in the graph to the left represents the grayscale value for each of the CCD-pixels along a column through the centre of the dots. The ring markers show the polynomial fit and the crosses indicate the calculated centre of the dot. The graph to the right shows a magnified part of the graph to the left. The triangles show the graylevel in each CCD pixel, the dotted line shows the polynomial fit and the cross represents the centre of the dot.

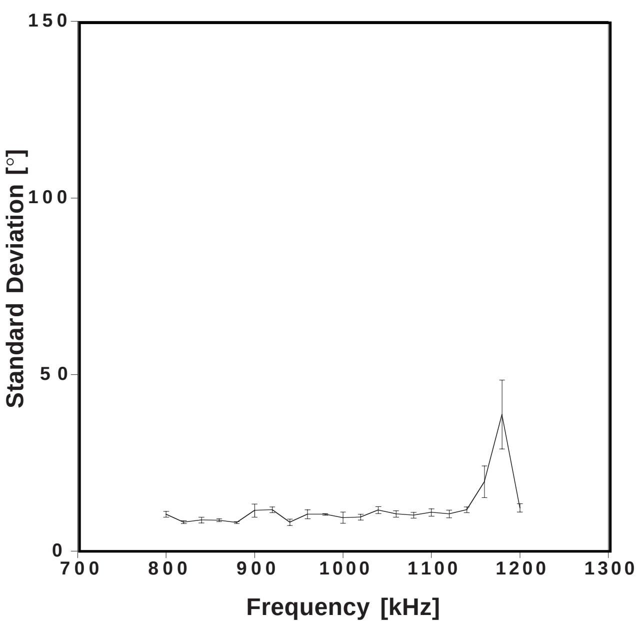

Figure 6. Measured droplet flight stability when the nozzle was stimulated at different frequencies. The measurements were conducted at 7 mm distance from the orifice of the nozzle. The amplitude of the stimulation signal is 10 Vpp.

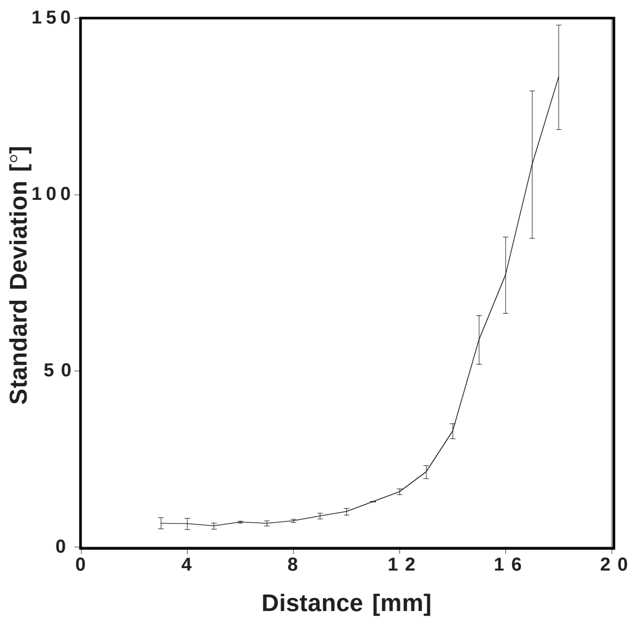

Figure 7. The measured droplet flight stability when the nozzle was stimulated with frequency of 1 MHz and the distance from the orifice of the nozzle to the point of measurement was varied. A non-linear change in measured standard deviation is detected when the distance from orifice is increased. The amplitude of the stimulation signal is 10 Vpp.

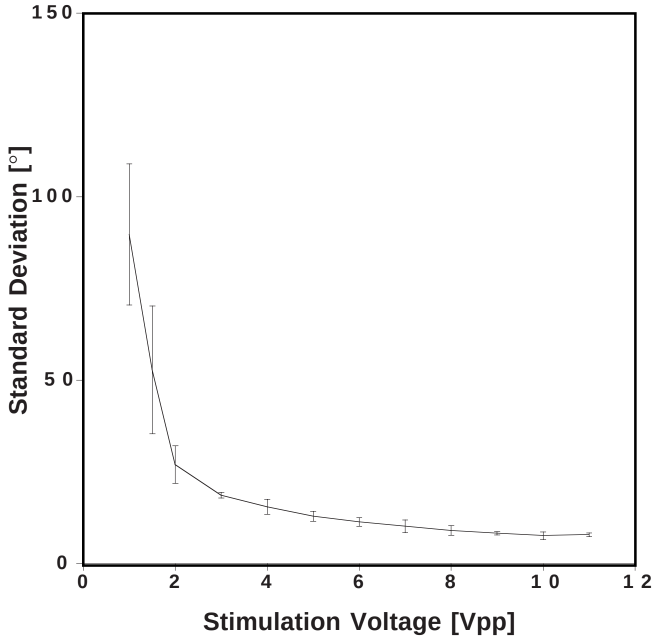

Figure 8. A plot of the influence of stimulation signal amplitude on the measured droplet flight stability measured at 7 mm distance from the nozzle. The standard deviation is decreasing rapidly for increased amplitudes when the voltage is below 4 Vpp. Five measurements were conducted at each voltage and the graph show the mean as well as the standard deviation as error bars. The frequency of the stimulation signal is 1 MHz.

imation of the center of the dot. The distance between dots on paper was then calculated by determining the distance between the identified centers of the dots.

Results and Discussion

Droplet Flight Stability Measurement. The nozzle showed high droplet flight stability for stimulation frequencies up to 1140-kHz (Fig. 6). The 1.0 MHz stimulation frequency was selected for the experiments because it showed good stability and it is the frequency at which the nozzle is intended to be used. The error bars were computed as the standard deviation for five consecutive measurement series.

The measured value of droplet flight stability depends on the distance from the orifice of the nozzle to the point where the measurement is conducted (Fig. 7). The measured droplet flight stability for high stimulation amplitudes close to the nozzle is close to the noise level in the measurement set-up and the droplet flight stability for low stimulation amplitudes measured far from the nozzle is greatly influenced by the air resistance. The repeatability of the measurement at low stabilities is also reduced (wider error bars). It is interesting to allow droplets to travel for some distance before the measurement is conducted to allow the initially small velocity differences to develop to a detectable variation in droplet-to-droplet distance. It is, however, not the sole aim of the study to measure the influence of air resistance, and therefore the distance to the point of measurement is chosen to be somewhere in between. The droplet flight stability does also depend on the stimulation frequency and the properties of the ink, which will influence the distance at which measurements could be conducted. To enable measurement under these varying circumstances the droplet flight stability is measured at 7 mm from the nozzle.

The results of the droplet flight stability measurement for varying stimulation voltages in Fig. 8 show that the stability increases rapidly when the voltage is increased from 1 to 4 V. The stability improvement is less dramatic when the voltage is increased further. However, the results show that it is beneficial to use a high stimulation amplitude to ensure a high droplet flight stability.

Droplet Placement. The size of the region for synchronization between stimulation signal and control voltage

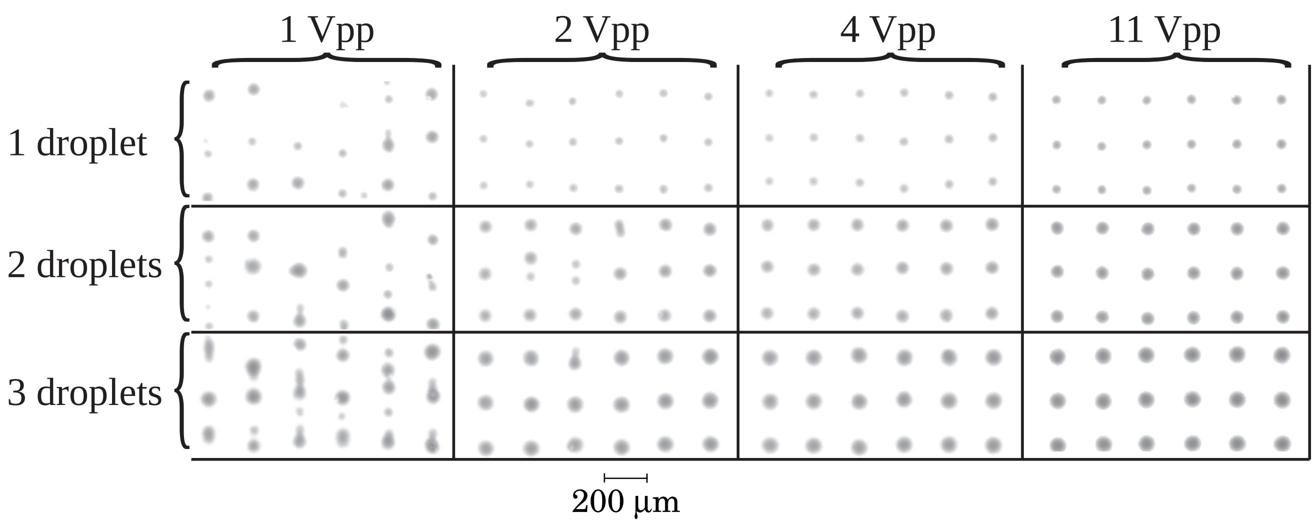

Figure 9. Examples of dots for four different stimulation voltages 1 Vpp, 2 Vpp, 4 Vpp and 11 Vpp. The top part of the figure shows a part of an image with one droplet of ink deposited in every other pixel and in the lower parts are parts of images shown with two and three droplets of ink deposited in every other pixel. The image consists of parts from three different images for each stimulation voltage. There was a slight variation in lighting conditions between the different images resulting in minor density variations in the reproduction.

where complete charging and discharging of droplets is possible was experimentally found to be 115°. Therefore the test images should be printed under ideal settings for at least two of the six synchronization settings for high droplet flight stabilities, which was confirmed during the experiments. For the lowest droplet flight stabilities all regions showed relatively poor performance, but it was, however, possible to select one region that was slightly better then the others. The poor performance may, however, depend not only on the low flight stability but also on poor charging conditions due to a more unstable jet cutoff. The satellite droplets were backward merging for all used stimulation voltages.

The presence of droplet placement errors was found to be closely related to the droplet flight stability since the number of errors was substantially reduced when the stimulation voltage was increased. Figure 9 illustrates the different errors that can take place. For higher droplet flight stabilities (4 and 11 Vpp) the errors show up as slightly misplaced dots. The correct number of droplets reach each pixel because the size of the dots does not vary. For lower stabilities (1 and 2 Vpp) both misplaced dots and erroneous numbers of droplets in the pixels exist. The erroneous numbers of droplets results in varying dot sizes within an area of constant numbers of droplets per pixel. We can also see in the printout at 2 Vpp stimulation that for some occasions the correct number of droplets are aimed at a pixel but hit the paper separately. This can be an effect of both unstable droplet flight and unstable droplet formation, resulting in a slight charge in either of the droplets. For 1 Vpp stimulation there are large variations in both droplet placement and number of droplets that reach the pixels. No errors concerning the number of droplets per pixel were found when the droplet flight stability was less than 15°, measured at 7 mm from the nozzle. This condition was reached for a used stimulation voltage of 4 Vpp for the nozzle. Figures 10–12 show the variation in droplet placement accuracy for 1, 2, and 3 droplets/pixel at different stimulation voltages.

The analysis method is somewhat simplified because it detects only spots on the paper and does not take into account the variations of spot size that take place at low stability levels. A pixel in an image that was printed with three droplets of ink per pixel may show up as two or even three spots on the paper when the droplet flight stability is low (1 and 2 Vpp in Fig. 9).

For the case of correct number of droplets per pixel (4 Vpp and above), the placement accuracy is slightly less for a single droplet per pixel compared to 2 or 3 droplets/pixel. This can be explained by the fact that a single droplet is more affected by air drag than a larger one. Two and three droplets will merge in flight due to air resistance[7] and reach the paper as a single larger droplet thus less sensitive to, for instance, air currents around the drum.

The droplet flight stability was increased when the amplitude of the stimulation signal was increased, and our measurements did not show the presence of a maximum level of amplitude above where the stability decreases. In a separate experiment, the stimulation voltage was increased to 100 Vpp in 10 V steps and stability was measured for each of the amplitudes. A small increase of flight stability was experienced for each step, but the stability soon reached

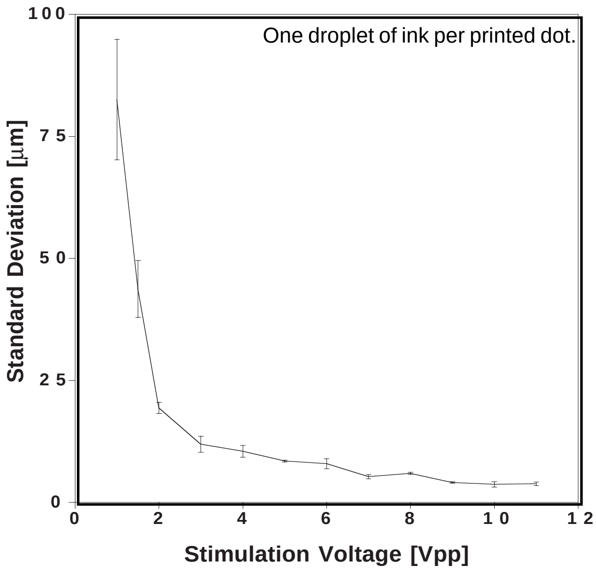

Figure 10. The standard deviation for distance between dots on paper. The dots contain one droplet of ink. The mean value for repeated measurements is represented by the line and the standard deviation for the measurements is presented as error bars.

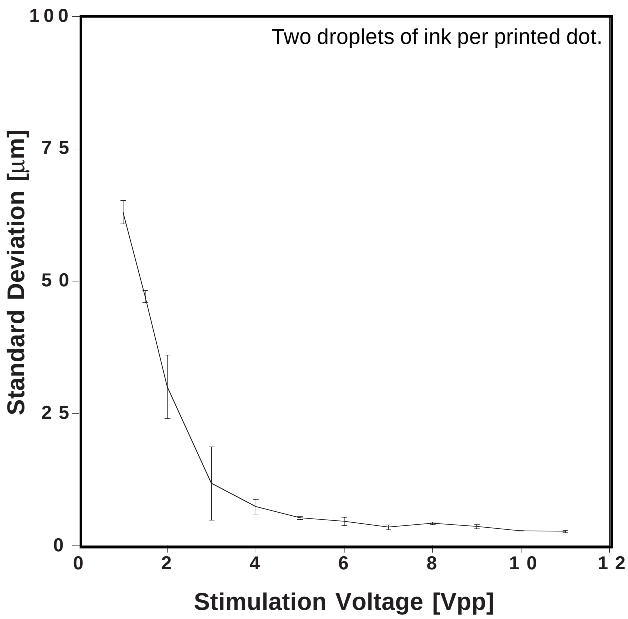

Figure 11. The standard deviation for distance between dots on paper. The dots contain two droplets of ink. The mean value for repeated measurements is represented by the line and the standard deviation for the measurements is presented as error bars.

the noise level for the system and no improvements could be detected. It was found however, that the crystal experienced a raised temperature and this influenced the properties of the ink when the stimulation voltage was above 20 Vpp. The increased temperature influences both viscosity and surface tension and thereby the velocity of jet. Because all these parameters determine the break-up time[3] the synchronization between droplet cut-off and droplet charge will be affected. A steady state is normally reached after some minutes.

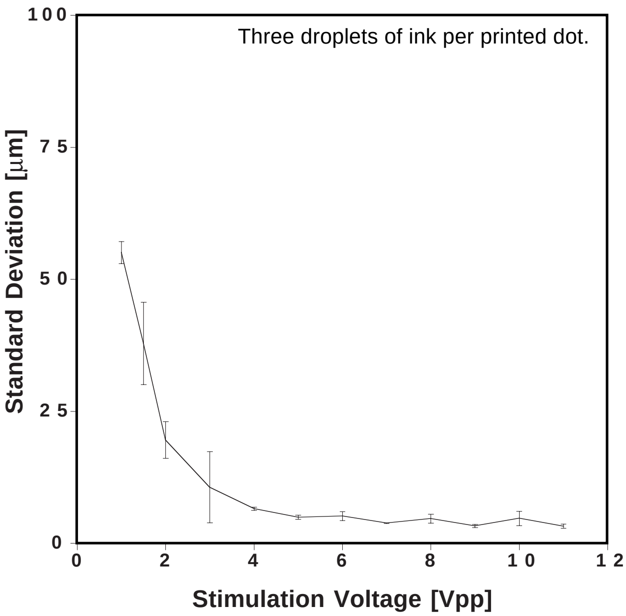

Figure 12. The standard deviation for distance between dots on paper. The dots contain three droplets of ink. The mean value for repeated measurements is represented by the line and the standard deviation for the measurements is presented as error bars.

Conclusions

This study shows that an increase of the stimulation signal amplitude will increase the droplet flight stability, and by doing, also increase the accuracy of droplet placement. When the standard deviation for time between droplets is 15° or less, measured at 7 mm from the orifice, the level of droplet placement error is very low. The visually inspected images reveal no errors in the amount of ink that is deposited in the pixels. This level of droplet flight stability is reached for the nozzle used, when the amplitude of the stimulation signal is 4 Vpp. It is beneficial to use stimulation voltage as high as possible as long as the piezoelectric crystals do not become hot, which may affect the ink properties.

References

1. C. H. Hertz and B. A. Samuelsson, Ink jet printing of high quality color images", *J. Imaging Technol.* **15,** 141 (1989).
2. I. W. S. Rayleigh, On the stability of jets, *Proc. London Math. Soc.*, **10,** 4 (1879).
3. C. Weber, Zum Zerfall eines Flüssigkeitsstrahles, *Z. Angew. Math. Mech.* **11,** 136 (1931).
4. A. Haenlein, Über den Zerfall eines Flüssigkeitsstrahles, *Forsch. Gebiete Ingeieurw* **2**(4) 139 (1939).
5. C. A. Bruce, Dependence of ink jet dynamics on fluid characteristics, *IBM J. Res. Develop.* **20,** 258 (1976).
6. M. Orme, On the genesis of droplet stream microspeed dispersions, *Phys. Fluids* **3,** 2936 (1991).
7. L. Palm and J. Nilsson, An optical method for measuring drop flight stability in a continuous ink jet, *J. Imaging Sci. Technol.* **41,** 48 (1997).
8. B. Samulelsson, An investigation of the halftone method, Technical Report No. 1/87, LUTEDX/(TEEM-1034), Department of Electrical Measurements, Lund Institute of Technology (1987).
9. A. Atten and S. Oliveri, Charging of drops formed by circular jet breakup, *J. Electrostat.*, **29,** 73 (1992).
10. G. Rydgren, Alphnumeric ink jet printing by ultrasonic jet control—Part 1, Technical Report No. 5/85, LUTEDX/(TEEM-1028), Department of Electrical Measurements, Lund Institute of Technology (1985).
11. J. Nilsson and L. Palm, "Electrical properties of the droplet formation of a continuous ink jet", in *Proc. IS&T's NIP 12*, IS&T, Springfield, VA (1996).
12. G. Rydgren, Alphnumeric ink jet printing by ultrasonic jet control—Part 2, Technical Report No. 1/86, LUTEDX/(TEEM-1028), Department of Electrical Measurements, Lund Institute of Technology (1986).
13. T. G. Twardeck, Effect of parameter variations on drop placement in an electrostatic ink jet printer, *IBM J. Res. Develop.* **21,** 31 (1977).
14. G. L. Fillmore, W. L. Buehner and D. L. West, Drop charging and deflection in an electrostatic ink jet printer, *IBM J. Res. Develop.* **21,** 37 (1977).
15. Handbook of Chemistry and Physics, 72nd ed., CRC, Boca Raton, FL, 1992–1993, ISSN 0363-3055.