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An Optical Method for Measuring Drop Flight Stability in a Continuous Ink Jet

Lars Palm* and Johan Nilsson*

Dept. of Electrical Measurements, Lund Institute of Technology, PO Box 118, SE-221 00 Lund, Sweden, E-mail: Lars.Palm@elmat.lth.se

This paper describes an optical method for improved drop velocity stability measurement to be used in continuous ink jet printing applications. Stable drop formation is demanded in continuous ink jet printing and it is normally achieved by introducing mechanical vibrations from a piezoelectric crystal onto the jet emerging from a nozzle. The method in use today to obtain information about the stability of drop velocity is to view the drops in stroboscopic light. This method does not provide quantified information about the level of drop velocity stability and the roughness of the method makes comparison between different levels of stability subjective and hence difficult. In our method we illuminate the drop train with a continuous HeNe-laser to create a shadow image of the drops. This image is magnified through a microscope and projected onto the light sensitive area of a PIN photodiode-based detector the output of which is sampled by a digitizing oscilloscope. The sampled data is used to calculate the standard deviation of time between drops and this value is used as a measure of drop velocity stability. Our method is primarily developed to measure the stability of drop velocity of drops with a diameter of 15 µm at crystal excitation frequencies in the interval of 800 to 1400 kHz. However, the set-up can easily measure drop velocity stability for different sizes of drops by simply changing the magnification of the microscope. Measurements with our method show that an increased excitation signal amplitude will result in a higher level of stability. The drop velocity is to a great extent decreased by air resistance as the drops travel. The presence of good and poor stimulation frequencies for nozzle systems is shown, and the frequencies are indicated by low and high levels of standard deviation for time between drops.

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Introduction

The Hertz principle for continuous ink-jet printers was invented at our university by the late Professor Hellmuth Hertz who announced the method in 1967. The method was intended primarily for printing of graphical images and is today in use in commercially available continuous ink-jet printers for high-quality hardcopy output.

The ink jet is created by forcing conductive ink through a glass nozzle, and the ink is ejected at the orifice as a jet that naturally breaks into drops. The formation of drops is enhanced and stabilized with the aid of a vibrating piezoelectric crystal that mechanically introduces vibrations onto the liquid jet. To make it possible to charge drops individually, a control electrode is positioned at the point of drop formation. When a positive control voltage is fed to the control electrode, this attracts charges of the opposite sign to the drop about to be cutoff [see Fig. 1(a)].

The uncharged drops are used to form the print, and a high voltage across the deflection electrodes is used to deflect the unwanted charged drops. The deflection voltage forces the charged drops toward the base of the knife edge, and, because suction is applied to the porous electrode, no fluid will remain on the surface of the electrode.

It is essential that the control voltage is applied to the control electrodes in phase with the drop formation process to deflect drops properly [see Fig. 1(a)]. Drops will be charged to unwanted levels if the control voltage is out of synchronization with the drop formation process. This will, in turn, affect the deflection of drops and drops may hit the top of the knife edge causing splatter that may stain the paper [see Fig. 1(b)]. Unwanted drops may also pass above the knife edge and result in incorrect density-levels in a pixel.

A similar problem can occur if the drop velocity fluctuates within the drop train—a variation that can make drops merge in flight. The wanted deflection toward the base of the knife edge for a charged drop will be disrupted if it merges with an uncharged drop in flight due to the doubled mass but constant charge. The merged drop may cause stains or incorrect density levels similar to the previous synchronization problem.

Today, the drop formation process and the deflection mechanism are scrutinized by viewing the drops in stroboscopic light, and the level of drop velocity stability is determined subjectively from the level of fuzziness in the drop images (see Fig. 2). If the drops appear sharp this is because they are illuminated at exactly the same position each time the stroboscopic light flashes. Because the stroboscopic light is triggered by the excitation signal fed to the piezoelectric crystal, the sharp image is an indicator of high stability. Poor stability will be represented by a smeared image because the drop image represents a mean value of the drop positions at the time of illumination. The sequences with excitation amplitude V_p of 6 or 7 V in Fig. 2 subjectively indicate that the level of stability would be sufficient for printing.

Drop formation from capillary streams have been studied since the late nineteenth century. The first theoretical approach on the theory of drop formation was presented by Lord Rayleigh[1] in 1879, in which he described the growth of temporal disturbances on a capillary stream.

An early application of drop measurement using sparks for the imaging of individual drops, stroboscopic measurements on drops, and measurements on individual drops with the aid of a light beam and photocell was reported by Crane, Birch, and McCormack.[2] Their measurements were, however, conducted on large drops with a diameter of 960

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*IS&T Member

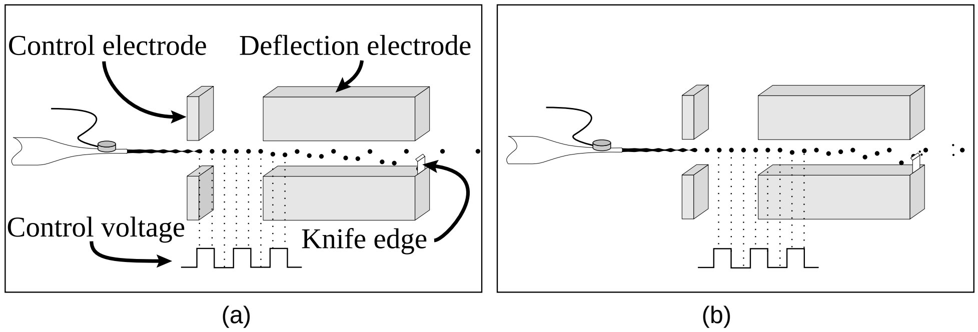

Figure 1. (a) Normal deflection where the control voltage is applied in phase with the drop generation. (b) Incorrect deflection due to poor synchronization between control voltage and drop generation causing stains on the printout.

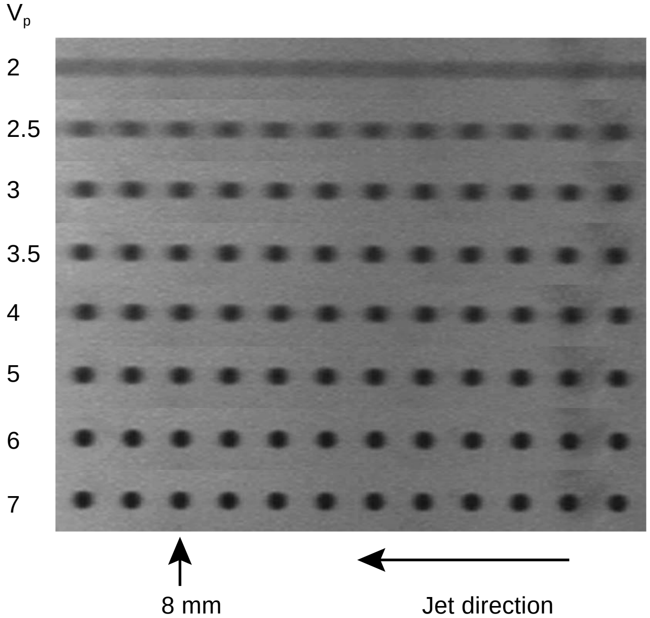

Figure 2. Drops created with a frequency of 860 kHz viewed in stroboscopic light 8 mm from the orifice. The level of stability increases downward in the image with increased amplitude of the excitation signal. The excitation amplitude for each sequence V_p is displayed to the left of the image. The drops (Ø = 15µm) travel to the left with a speed of 50 m/s.

µm. Drop formation analysis based on images of drops viewed in stroboscopic light has also been reported, for example, by Donnelly and Glaberson[3] as well as Goedde and Yuen.[4] The use of a flash, or a spark, and camera to capture images of individual drops have been reported by Rutland and Jameson[5] as well as by McCarthy and Molloy.[6]

In a study of the effects of the jet's physical properties, Bruce[7] used a stroboscopic system to study the influence of viscosity and surface tension on jet velocity, separation length and drop formation stability. A microscope was used to observe the drops in stroboscopic light created with an LED at 1 pulse/drop period. Drop formation stability was measured by decreasing the voltage to the piezoelectric crystal until the drop image no longer became clear. The minimum voltage, required to get a time-stable jitterfree stream of drops, was used as a measure of drop formation stability. The study showed that drop formation stability was unaffected by changes in viscosity and surface tension in the range that was applied in the experiments.

The influence on jet behavior by stimulation of the jet with both the fundamental and an added harmonic was studied by Chaudhary and Redekopp[8] as a way to suppress the formation of satellite drops. Measurements concerning these theories were conducted by Chaudhary and Maxworthy[9] on drops with a diameter of 40 µm with the use of stroboscopic light and a TV camera.

The size and velocity distribution for a stream of droplets with no satellites present has been measured by Chin and colleagues.[10] The measurements were conducted on small drops (Ø = 50 µm) with the aid of a Phase/Doppler particle analyser (PDPA).

Speed differences for drops as a result of the applied perturbation have been studied, and the use of amplitude-modulated excitation signals has been suggested to establish less variance in drop speed by Orme and colleagues.[11–14] The setup used in their experiments consists of a flight tube, usually evacuated to background pressures of 10^{-5} torr, with observation stations at 26-cm and 5.4-m distance from the orifice. A continuous laser beam is sent through the drop train at the observation stations and a photomultiplier positioned behind a slit detects dips in the received light intensity as a result of drops passing through the beam. The orifices used in this study have diameters in the range of 78 to 200 µm. The authors have also reported on the use of a pulsed dye laser to illuminate and photograph individual drops.

Another application to detect individual drops is presented in a technical note by Qian, Gou, and Yu[15] in which they measured the angular dispersion of the jet with the aid of a laser beam and stacked optical fibers. An intensity dip in the received laser light for one of the optical fibers was seen as an indication of a discrete level of deflection. The presented experimental data were gathered with large drops (Ø = 1.35 mm), but the authors stated that the drop diameter can be decreased to 120 µm and still be detected by the same setup.

The use of stroboscopic light to measure stability does not make it possible to assess objective quantified information on drop velocity stability nor does it facilitate the comparison of stability levels for drops. A step forward in the direction of objective analysis of drop velocity stability based on the knowledge of behavior of individual drops has been taken by Orme and colleagues.[11–14] However, their method has not been reported for the size of drops (Ø = 15 µm), the drop velocity (50 m/s), or for the drop formation frequency (≈1 MHz) used in continuous ink-jet printers.

To establish a quantitative analysis of the drop formation process, it is essential to have knowledge of drop behavior based on individual drops. Our method to determine the level of stability concerning drop velocity provides this knowledge. We determine the time between drops by illuminating the drop train with a continuous HeNe laser and measuring the drop-to-drop time by studying light variations in the shadow image. This approach to measuring

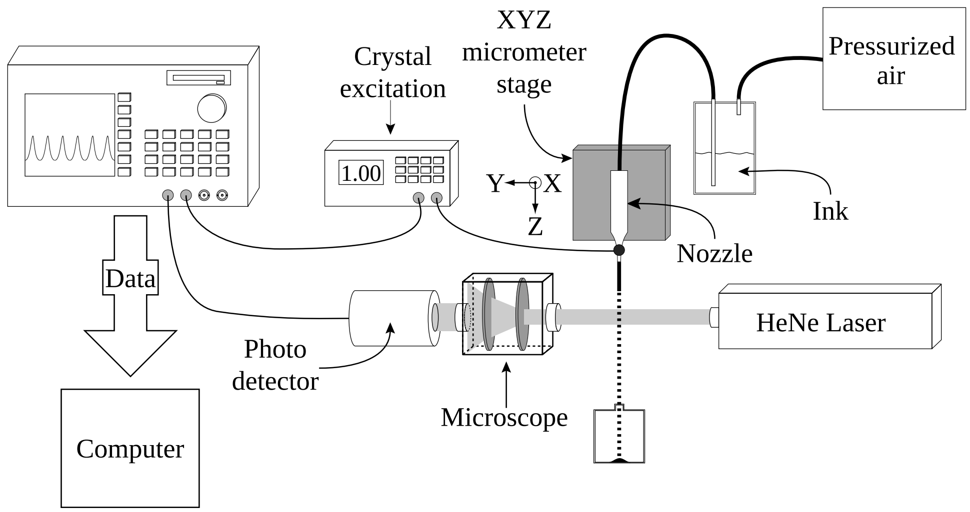

Figure 3. Drop measurement setup.

velocity variations is possible since variations in drop-to-drop time are proportional to variations in drop velocity. Our measurements were conducted on small drops with a diameter of approximately 15 μm traveling in free air to resemble the working conditions for a continuous ink-jet printer.

Materials and Methods

We use a continuous 0.95-mW HeNe laser (Novette 1508, Uniphase, USA) to create a shadow image of the drops that is projected onto the light-sensitive area of a photodetector with the aid of a microscope. The laser is mounted in a fix position where the laser beam is directed straight to the light-sensitive area of the photodetector. To focus the shadow image on the sensitive area of the detector an XYZ micrometer stage is used to move the nozzle in the y direction (see Fig. 3).

In our setup we have used two types of glass nozzles (Siemens-Elema, Solna, Sweden) and (IRIS Graphics, Mass., USA) both with an orifice of 10 μm supplied either with an ink substitute (Storage Fluid, Siemens-Elema, Sweden) which has the same physical properties as those of ink, but it does not contain any dye, or with a black ink (Siemens-Elema, Sweden). We have used pressurized air to produce the ink driving pressure of 40 atm. in all experiments.

The deflection electrodes do somewhat protect the jet from influence by external airflow. In some experiments the electrode system has been replaced by a brass tube with a slit to compare their air drag protection. Some experiments have also been conducted with neither electrode system nor brass tube to study if the airflow disturbs the individual velocity distribution or just alters the direction of the jet.

The position of the nozzle in the direction of the jet (z axis) is adjustable with the use of the micrometer stage to enable studies of drop velocities at various distances from the orifice. The orifice of the nozzle is initially positioned at the point of laser illumination to adjust the focus of the system, but the nozzle can be moved 25 mm backward, facilitating studies of drop behavior throughout the flight. Because the paper-carrying drum in a continuous ink-jet printer is usually positioned around 20 mm from the orifice, it is possible to register the drops during a relevant flight-length interval.

The magnification of the optical system is set to 29× to ascertain that the shadow image of one drop has the same area as the light-sensitive area of the photodetector. The passage of a drop will result in a dip in the laser light, which is detected with the aid of a PIN diode (2216-02, Hamamatsu, Japan) with sensitive-area diameter of 390 μm corresponding to a circular sensitive area of 0.12 mm^2. We use a microscope (SMZ-2T, Nikon, Japan) to magnify the drops because the instrument can be used both for observation and for measurement with a slight modification of the setup. An LED may be mounted in the laser position to make it possible to easily view the drops in stroboscopic light—an arrangement that makes our setup very versatile.

The drop train is moved through the laser beam in the direction of the x axis by the aid of the micrometer stage to find the maximum output for the detector. A maximum is reached when the shadow image of a drop covers the sensitive area of the detector. The diode output is amplified in two steps: first with an FET stage and, second, with three cascaded wideband high-frequency amplifiers (NE 5205, Signetics, USA) each with a gain of 20 dB. These stages amplify the output from the photodiode 50,000×.

The detector output is connected to a digital oscilloscope (Scopestation LS-140, LeCroy, USA) with a recording length of 20,000 samples (8 bit/sample). An example of the detector output as displayed on the oscilloscope can be studied in Fig. 4. Naturally, measuring with high time resolution is important to detect small variations in time between drops. The maximum sampling speed for single shot events for the Scopestation is 200 MS/s, which sets the maximum time resolution to 5 ns. This sampling interval makes it possible to distinguish variations in drop-to-drop times larger than 0.5% of the period for a frequency of 1 MHz. A recording length of 20,000 samples at a sampling frequency of 200 MS/s makes it possible to gather information about 100 consecutive drops at the frequency of 1 MHz. It is of interest to study drops created at excitation frequencies in the range of 500 to 1500 kHz. Because of the sampling frequency, the detectable deviations at the above frequency limits are 0.25% and 0.75%.

The measured data were transferred to a computer (Power Macintosh 8100/110, Apple, USA) where a LabView application (National Instruments, USA) was developed to distinguish peaks in the measured data. A peak in the data corresponds to a drop in the shadow image covering the detector area, and the LabView application produces a vector consisting of drop-to-drop times used for statistical calculations.

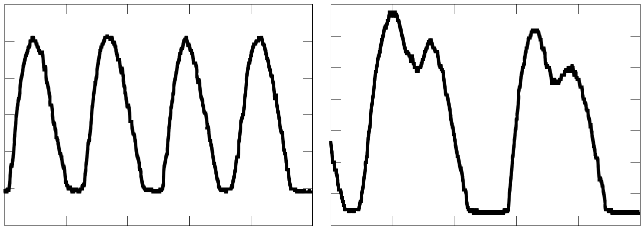

Figure 4. Detector signal, as displayed on the oscilloscope, for drops with high stability (*left*) and low stability (*right*).

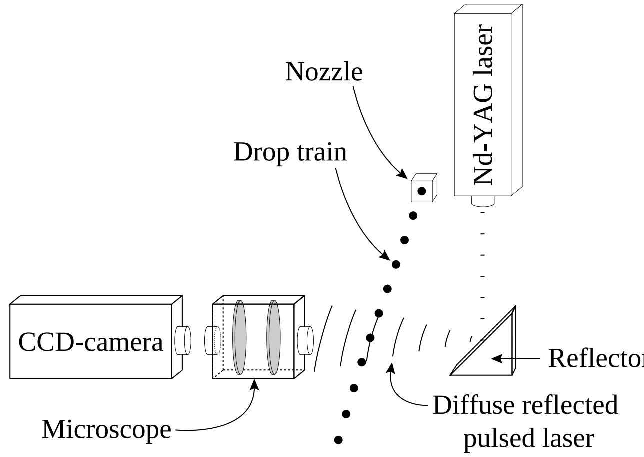

Figure 5. Drop imaging setup.

To determine the noise level in the measurement setup, a 2-mW pulsed diode laser (LSX, LaserMax, USA) was used instead of the continuous HeNe laser. The pulsing of the laser was fixed by a crystal-controlled frequency generator (HP 3324A, Hewlett Packard, USA). With the use of the pulsed laser to simulate a drop train with very high stability, the measured standard deviation for time between peaks was used as the noise level for the setup.

To verify that drop sizes and drop-to-drop distances could vary at low stabilities, as indicated by the oscilloscope readout, the setup was modified slightly to make possible image capture of individual drops. The drop train was illuminated by a pulsed Nd-YAG laser (Continuum PY61C, Continuum, USA) that every 100 ms emits 100-ps-long light pulses with an energy content of 70 mJ (see Fig. 5). The light pulses were directed to a white surface, and the diffuse reflected light from the surface was used to illuminate the drop train. The drop images were captured with a CCD camera (C5405, Hamamatsu, Japan) with a resolution of 756×485 pixels on a 1/2-in. chip.

The pictures of drops, shown in Fig. 6, support the measurement data because a measured high level of stability is represented by equally sized drops at constant distance from each other and a low level is represented by different drop sizes, which is due to merged drops and varying drop-to-drop distances.

Results and Discussion

The aim of this investigation was to characterize objectively the performance of nozzles and to study the velocity variations from drop-to-drop to improve print quality by choosing the optimal system settings that generate low-drop-velocity variations. This measurement method will facilitate more precise knowledge of drop-speed behavior for various excitation frequencies and for various inks used in a nozzle. This knowledge is especially important during nozzle and ink development.

The standard deviation for drop-to-drop distances in time was used as a measure of stability with low standard deviation indicating high stability and high standard deviation indicating poor stability. The measurement output must be a relative measure of stability to enable comparison between standard deviations for nozzles working at different frequencies. One way to express the measured standard deviation for comparison is to relate it to the period of the selected crystal excitation frequency. By doing this, the measurement output is presented in degrees, where 360° represents the period of the excitation frequency.

When the pulsed diode laser was used to simulate a drop train with very high stability, the measured standard deviation was characterized as the noise level in the detector setup. The standard deviation of time between drops was approximately 10 ns over the entire frequency range (800 to 1400 kHz). This level was considered to be the noise level, indicating that standard deviations below this could not be detected.

The normal electrode configuration for the continuous ink-jet printer protects the jet somewhat from external air flows that alter the direction of the jet. However, the stability of drop velocity does not seem affected by the absence of the electrode configuration. No obvious decrease in stability is seen when the electrode system is replaced by a brass tube or even when there is no air drag protection at all. A problem we encountered was when external air flow moved the jet and, hence, the shadow image moved away from the sensitive area of the detector.

The initial differences in drop velocity are small and thus difficult to measure at the point of drop formation, but the difference in drop-to-drop distance will increase linearly over time as the drops travel, if the drops travel in vacuum. Two slightly different velocities for the two drops in a pair, in theory, will make the distance between the drops change linearly over time. In practice, air resistance will affect the drop flight stability resulting in a non-linear change in distance between drops (see Fig. 7). Therefore we should measure at a distance from the orifice and avoid noise from air resistance as much as possible. Measurements showed empirically that distances of 8 to 10 mm from the orifice meet demands for good stimulation frequencies. The optimum measurement distance will vary, however, with the level of stability. For poor stimulation frequencies, it is necessary to measure closer to the orifice. The data presented in Figs. 7-9 was gathered during multiple measurements and the graphs represent the mean of these measurements. The error bars show the standard deviation.

Most nozzle systems are designed to operate at frequencies around 1 MHz. The excitation frequency supplied to the piezoelectric crystal therefore was set to frequencies in the range of 800 to 1400 kHz to enable us to study the

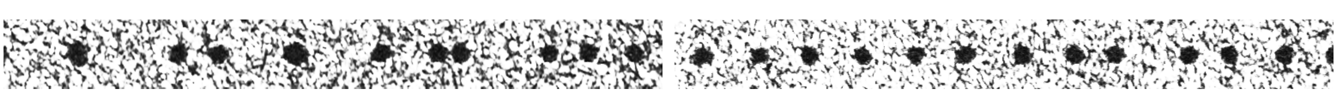

Figure 6. Pictures of individual drops at low- (*left*) and high- (*right*) stability levels with an excitation frequency of 860 kHz at 8-mm distance from the orifice. The two levels of stability were achieved by varying the excitation voltage.

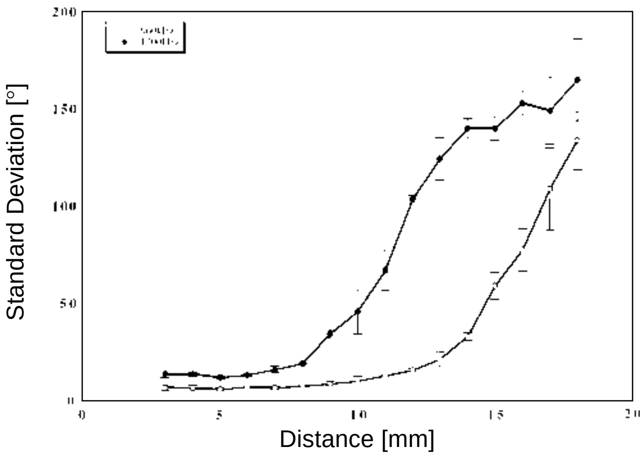

Figure 7. A graph of the influence of flight distance on drop velocity stability for a nozzle working at two frequencies when supplied with storage fluid. The stability was found to decrease dramatically when the measurements were conducted more than 10 mm from the orifice when 1200 kHz was used as excitation frequency. However for the frequency of 960 kHz the same decrease in stability was experienced but further away from the orifice. These frequencies are marked in Fig. 8 where the same nozzle has been studied at constant distance from the orifice but at different frequencies. The error bars show the standard deviation for three different measurements at each distance.

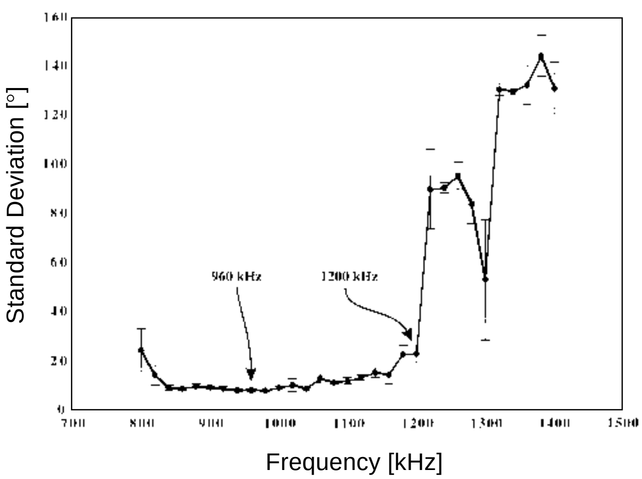

Figure 8. A graph of the frequency behavior for a nozzle measured 10 mm from the orifice when the nozzle was supplied with storage fluid. The plot shows the presence of good (around 960 kHz) and poor (above 1200 kHz) stimulation frequencies. The error bars show the standard deviation for three measurements at each frequency.

impact of frequency on the stability of drop velocity. The frequency interval was scanned in 20-kHz steps to get an overview of the presence of good and bad stimulation frequencies in the range. Scanning with higher resolution would show the topographical image of good and poor stimulation frequencies with even more detail, but it would also take proportionally longer time. The time needed to perform a frequency scan for the interval of 800 to 1400 kHz in 20-kHz steps is approximately 6 min. Hence, the choice of 20-kHz steps is a compromise between speed and resolution. This method shows that good and poor stimulation frequencies may be in close proximity (see Fig. 8).

The amplitude of the excitation signal has a major impact on the stability of the drop velocity. High voltages applied to the piezoelectric crystal produce larger mechanical perturbations on the jet that, in turn, increase the stability of the drop velocity. This is true unless the vibration of the crystal causes sinusoidal breakup of the jet. Another side effect from excessive stimulation of the crystal is that heating of the crystal, and therefore the ink, alters the properties of the ink. The effect on stability of modest variations of the crystal excitation signal are shown in Fig. 9. The stability increased almost 1 order of magnitude for the frequency of 960 kHz when the crystal excitation amplitude peak voltage was increased from 2 to 14 V.

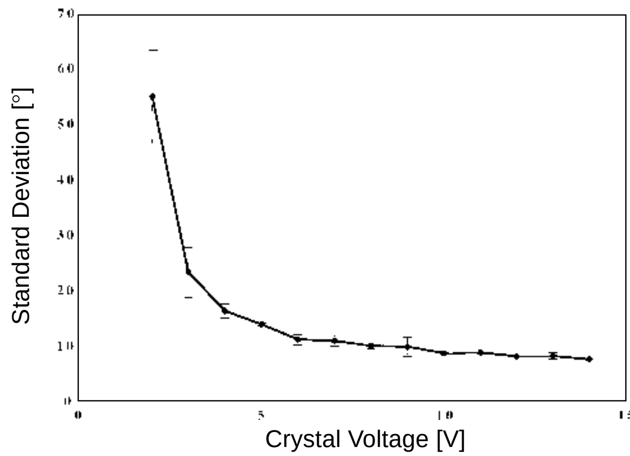

Figure 9. A plot of the increase of stability for an increase of excitation amplitude for a jet with a drop formation frequency of 960 kHz. The measurement was conducted 10 mm from the orifice with storage fluid as media. The error bars show the standard deviation for three separate measurements at each voltage.

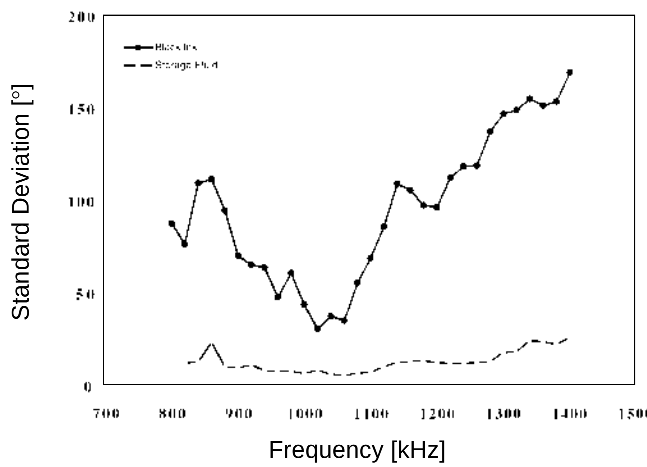

Figure 10. Frequency response for a nozzle supplied with two different fluids measured at 10 mm distance from the orifice.

The nozzle performance was repeatable if the same fluid was used, however, a change of fluid seriously influenced the performance. We used both storage fluid and black ink for our experiments and found that the drop velocity stability decreased when we used the black ink. Two frequency scans show this phenomenon in Fig. 10. Both scans were conducted at 10 mm from the orifice with an excitation frequency of 860 kHz at an amplitude of 8 V_p.

Images of individual drops were captured to verify the results obtained with the measurement setup. These images show the variation in drop-to-drop distances in a more detailed way than the stroboscopic light images are capable of doing (see Fig. 11). High-drop-velocity stability was represented by equally sized drops and constant drop-to-drop distances while low-drop-velocity stability was represented

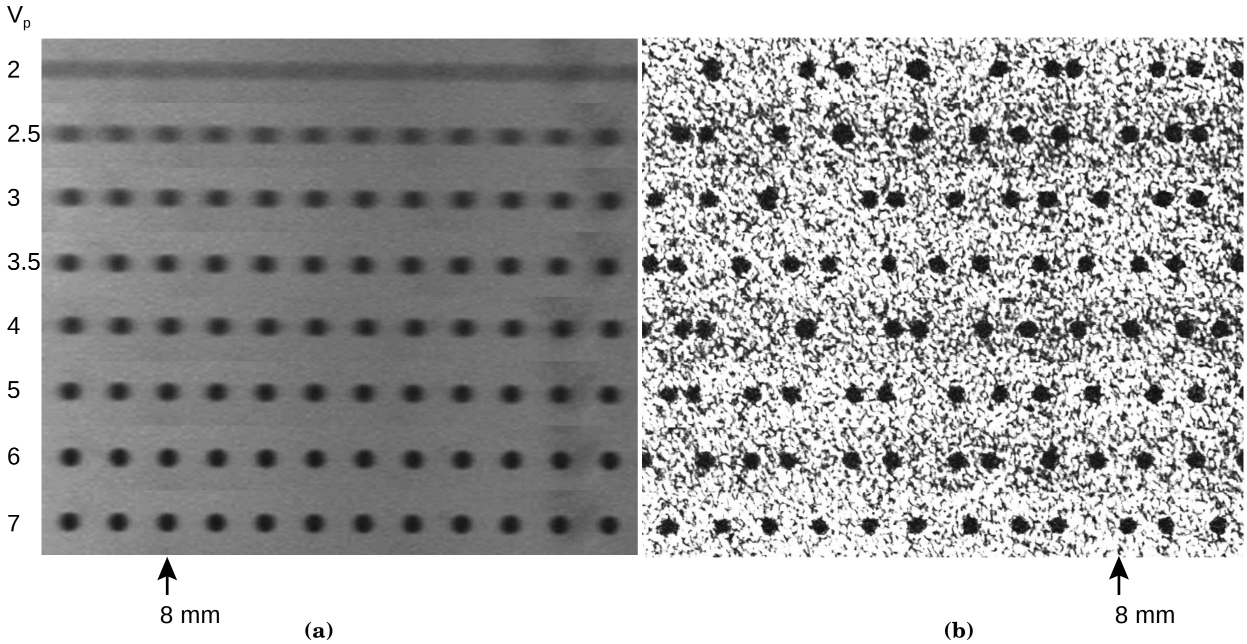

Figure 11. (a) Stroboscopic light images of drops (black ink) at the frequency of 860 kHz to the left and (b) real-time images to the right.

by varying drop sizes and drop-to-drop distances. One of the sequences shows almost constant drop size and a slight variation in drop-to-drop distances for the chosen excitation amplitude (3.5 V). This phenomenon has been observed for short periods of time for normally low stability excitations. It is, however, necessary to observe several drop periods to draw any conclusions on the stability level. This is valid for the analysis of drop velocity stability using either the measurement system or with the aid of drop images.

Conclusions

The proposed method provides objective and repeatable information about drop velocity stability from a continuous ink-jet nozzle system. This information is valuable both during development of the nozzle/stimulation system and ink and for quality control of the production process.

From our results the following conclusions can be drawn:

- Good and bad stimulation frequencies may be situated close to each other, probably due to resonance frequencies within the nozzle unit.
- A level of stimulation amplitude exists above which drop velocity stability does not increase significantly.
- Ink affects the drop velocity stability to a great extent.

The use of an ordinary microscope for magnification of the drop shadow images makes the setup simple and versatile, because the same microscope may be used for viewing the drops in stroboscopic light by adding a pulsed LED.

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