Electrical Properties of the Drop Formation of a Continuous Ink Jet

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Abstract

This paper deals with electrical characterization of the drop formation of a continuous ink jet. Methods are presented for investigations of the behavior of a nozzle system for different stimulation frequencies and for measurement of the width of the forbidden region for control voltage switching during the formation of a drop. The nozzles used in the investigations are glass nozzles from Siemens-Elema (Solna, Sweden). At 4.0 MPa ink pressure, 9.5 µm diameter jets are emerging with a velocity of around 50 m/s. The results show that the amount of stimulation introduced on the jet varies with the stimulation frequency due to mechanical resonance frequencies of the nozzle assembly. The results of the measurement of the forbidden region show that the width of the region is strongly influenced by the formation of satellite drops. The presented methods are a help in evaluating nozzle systems and in selecting suitable stimulation frequencies to ensure stable drop formation and controlled drop charging.

Introduction

In order to control the flight path of the drops in an ink jet printer based on continuous jets, electrical charging and deflection of the drops are used. The charging of the drops is possible since the ink is conductive. A ground terminal is in contact with the ink and a control electrode is placed around the point of drop formation (PODF) (Figure 1). When a voltage is applied to the electrode with respect to the ink, the jet will be charged due to electrostatic influence. The amount of charge induced is determined by the voltage, Vctl, connected to the charging electrode and the value of the capacitance, C, formed between the jet and the control electrode.

When the jet is cut off and a drop is formed the charge on the tip of the jet will be captured in the drop. The amount of charge transported by the drops will cause a charging current, Ic, through the ground terminal.

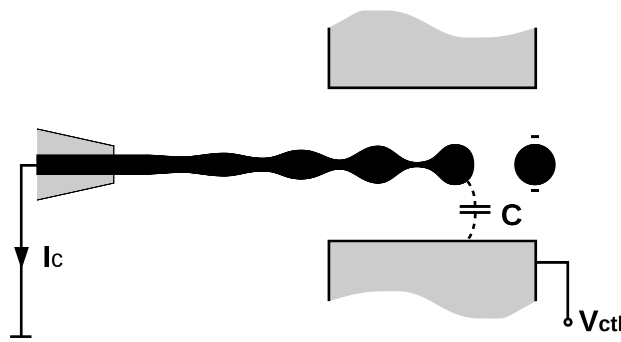

Figure 1. Electrical charging of a conducting continuous ink jet

The drop formation is stabilized by applying a mechanical vibration at around 1 MHz frequency to the jet, e.g. by a piezo-electric crystal. The drops formed will then be equal in size and the PODF will be well defined. When more than one nozzle is used in an ink jet printer it is desirable that the nozzles can be operated at the same drop formation frequency. The nozzle assembly together with the piezo-electric crystal make up a complex mechanical system. A vibration with 1.0 MHz frequency will have a wavelength of about 5 mm in glass and in metal, given the speed of sound of around 5000 m/s. This is considerably shorter than the physical dimensions of the nozzle assembly. The amount of stimulation applied to the jet will thus to a great extent depend on where the crystal is fit on the nozzle assembly, the actual dimensions of the parts of the assembly, the frequency behavior of the crystal and the frequency and amplitude of the voltage applied to the crystal. The stimulation introduced to the jet will in turn affect the stability in the drop formation.[1] Thus, it is necessary to examine the frequency behavior of a nozzle assembly to avoid frequencies where the resonance frequencies of the nozzle system counteract, resulting in weak stimulation.

In the ink jet printer the flight path of each individual drop is controlled. This can only be achieved if a drop can be completely charged or discharged during the drop formation period, 1 µs for 1 MHz drop formation frequency. The charging of a drop can be modeled on the charging of a capacitor through a resistor varying in time (Figure 2). The capacitor is formed between the drop to be formed and the charging electrode.

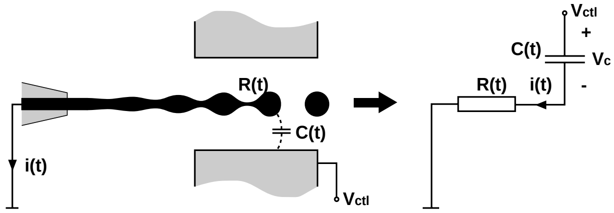

Figure 2. Electrical model of the charging of the drops

The resistance is increasing in time during the drop formation cycle due to the fact that the part connecting the drop to be formed to the rest of the jet gets thinner and thinner until the drop is finally cut off. To achieve complete electrical control of the drops in an ink jet printer it is essential that the switching of the control voltage occurs in the beginning of the drop formation cycle.[2] If the control voltage is switched too close to the drop cut-off, the resistance is too high and the drop will not be completely charged or discharged. The resulting semi-charged drop will be partially deflected in the deflection field leading to a misplaced spot on the recording paper. The region close to drop cut-off where no switching must occur is called the forbidden region.[2] The size of the region depends to a great extent on the resistivity of the ink and the way the filament connecting the outmost drop to the continuous jet is decreasing in size during the drop formation.

The value of the resistor in the charging model is determined by the total resistance from the ground connector to the tip of the conducting continuous jet. Since all the "necks" of the jet decrease in size during the formation of each drop, the resistance will increase periodically with time.

The forbidden region should be as narrow as possible in order to prevent small variations in the synchronization between the switching of the control voltage and the drop formation process from deteriorating the print quality.

In the following, electrical methods will be presented for the measurement of the amount of stimulation introduced on the jet and the width of the forbidden region.

Materials and Methods

All the experiments are performed using a Siemens-Elema nozzle with Siemens-Elema Storage Fluid as ink substitute (Siemens-Elema, Solna, Sweden). The resistivity of the Storage Fluid is 2 Ωm. The nozzle is operated at 4.0 MPa ink pressure resulting in a jet diameter of 9.5 µm with a velocity of 53 m/s unless otherwise stated.

Charging Current Measurement

The charging current can be measured either by connecting an picoamperemeter (Keithley 485, Keithley Instruments, inc., Cleveland, Ohio, USA) in the ground terminal or by collecting the charged drops and discharging them through the picoamperemeter to ground (Figure 3). The measurements presented here are conducted using the second alternative since it is then easier to isolate the drop collector in order to reduce noise and influence from leakage currents in the measurements.

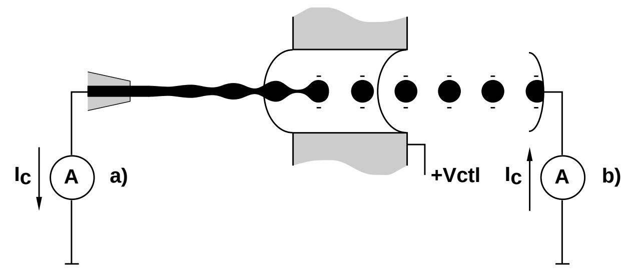

Figure 3. Charging current measurement. a) Through the ink ground terminal. b) Through discharging of the charged drop.

The size of the drop charge and thereby the size of the charging current can be estimated by approximating the charging tunnel and the ink jet with a cylindrical capacitor and computing the resulting charge on the drop as the charge on the capacitor, C, according to

$$q_d = V_{ctl} \cdot C \tag{1}$$

The charging current is then determined from

$$I_c = f_{cd} \cdot q_d \tag{2}$$

where f_{cd} is the frequency of charged drops, i.e., the number of drops charged per second. With a constant charging voltage all drops will charged and f_{cd} will be equal to f_d.

If the diameter of the undisturbed jet is taken as the diameter of the inner conductor, the capacitance between the drop to be formed and the charging electrode can be determined from

$$C = \frac{2\pi\varepsilon_0 l}{\ln\dfrac{D_c}{D_j}} \tag{3}$$

where D_c is the diameter of the charging tunnel and D_j is selected to the diameter of the undisturbed jet. The value of l is set equal to the length of the jet forming one drop. With D_c = 500 µm, D_j = 9.5 µm and l = 5.3 · D_j (assuming a jet velocity of 53 m/s and a drop formation frequency of 1.0 MHz) the capacitance will be 0.71 fF. With a charging voltage of 40 V the drop charge will be 28 fAs. At 1.0 MHz drop formation frequency, the charging current can be estimated at 28 nA. Due to the influence from the charge on the previously formed drops[3,4] the drop charge and thereby the charging current will theoretically be somewhat lower. The value of I_c has been measured to 31 nA for a jet and charging tunnel of the above sizes indicating that the cylindrical capacitor model is a reasonable approximation.

Measurement of the Variation in Jet Stimulation with Frequency

The distance, L, from nozzle to the PODF can be expressed as[5]

$$L = v \cdot T = \frac{v}{\beta} \ln\left(\frac{d}{2\delta_0}\right) \qquad (4)$$

where v is the jet velocity, T the time to jet break-off, ß the growth rate factor, d the jet diameter and δ_0 the stimulation amplitude applied at the nozzle exit. Thus, by measuring the distance to the PODF for different frequencies it is possible to determine how the amount of stimulation varies with the frequency.

The measurement can be accomplished electrically by using the fact that the amount of charge induced on the drops varies with the distance between the PODF and the charging electrode if the PODF is located outside the charging tunnel. Figure 4 shows the experimental set-up used in the following measurements. The charging electrode is made of a 2 mm thick brass plate. A 0.5 mm hole is drilled through the electrode forming a charging tunnel. The tip of the nozzle is positioned 2.0 mm from the charging electrode and the drops are aimed at the center of the 0.5 mm hole. The resulting charging current is then measured for varying stimulation frequencies when V_{ctl} is kept constant.

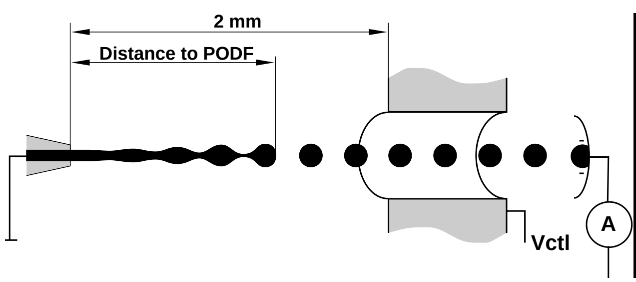

Figure 4. Experimental set-up for the measurement of the distance to the PODF.

Measurement of the Width of the Forbidden Region

Figure 5 shows the principle of the measurement. R is the resistance (schematic) to the drop to be formed during the drop formation period. A region measurement pulse (RMP) is applied during each drop formation cycle. The position of the leading edge of the pulse, τ, is varied over the drop formation cycle while the position of the trailing edge is kept constant to directly after drop cut-off. The forming drops will be charged during the on-time of the pulse. The charging of a drop is equal to the charging of the capacitor in the model (Figure 3). The capacitor is charged through the varying resistance, and the voltage across the capacitor V_C will increase and reach the level V_{CCO} when the drop is cut off. If the drop is fully charged V_{CCO} is equal to V_{ctl}. V_{CCO} is related to the drop charge according to equations 1 and 2. The resulting charging current is recorded for the different positions of the leading edge of the RMP.

If the resistance is low enough when the pulse is applied the drop will be fully charged. During the drop formation cycle, the resistance will increase and at some point it is no longer possible to fully charge the drop and the resulting charging current will decrease. This is an indication of that the leading edge of the RMP has reached the forbidden region.

The pulse output of the electronics is amplified by a MOSFET driver IC (Maxim MAX628) generating extremely short rise and fall times of around 5 ns. To be able to use this circuit, the charging voltage had to be reduced to 15V, thus lowering the maximum charging current. The RMP is applied to every second drop formed in order to reduce the influence from previously charged drops which further reduces the maximum charging current.

The position in time within the drop formation cycle will in the following be expressed as the phase within the drop formation cycle. One drop formation cycle is equal to 360 degrees where 0 degrees is defined as the time when the previous drop is cut off.

To be able to apply the RMP with the trailing edge positioned directly after drop cut-off, the phase of the drop formation cycle with respect to the crystal signal voltage has to be determined. This is accomplished by stepping a 22.5 degrees wide (on-time) phase measurement pulse (PMP) over the drop formation period. The resulting PMP charging current is recorded while the drop formation is viewed in stroboscopic light using a video camera connected to a microscope. The phase of the drop cut-off can be determined from the resulting PMP charging current curve and is found when the charging current reaches minimum. The result is verified on the video monitor. Photographs showing the drop formation in phase steps 0, 90, 180, (225) and 270 degrees together with the PMP charging current curves are incorporated in the result figures shown below. The RMP is applied and the length of the pulse is varied in 32 steps over the drop formation period while the resulting charging current for each step is recorded. Since the current measured is only a few nanoamperes at maximum, five consecutive readings from the picoamperemeter are averaged per step to reduce influence from noise.

Results and Discussion

Variations in Jet Stimulation with Frequency

Figure 6 shows the charging current calibration plot when the distance from the nozzle tip to the PODF was varied by varying the stimulation amplitude. The frequency of the stimulation was set to 1.0 MHz and the charging voltage was 40 V.

From the curve it can be seen that the maximum charging current is close to 31 nA and is found when the PODF has entered the charging tunnel.

Figure 7 shows the behavior of a nozzle when the stimulation frequency is varied for two different jet velocities. The ink pressures were 3.5 MPa (above) and 4.0 MPa (below) generating jets at 48 m/s and 53 m/s. The theoretical

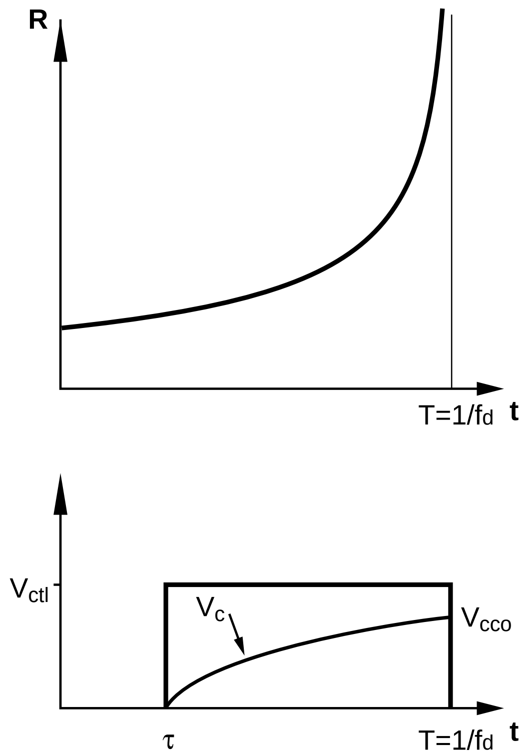

Figure 5. Principle for the applying of the region measurement pulse (RMP). The drop is charged during the on-time of the pulse.

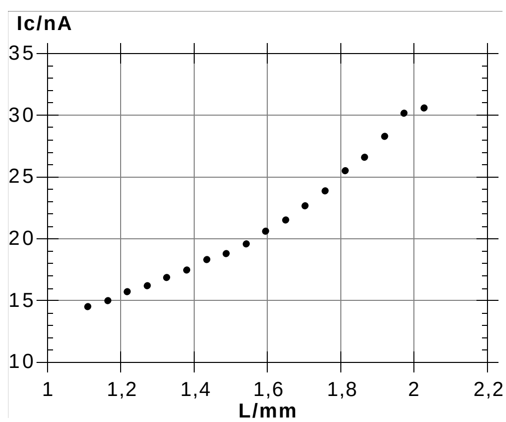

Figure 6. Charging current vs. the distance to the PODF for a 9.5 µm jet traveling at a velocity of 53 m/s. The stimulation frequency was set at 1.0 MHz and the charging voltage was 40 V.

maximum drop formation frequencies are 1.61 MHz and 1.79 MHz, respectively.

The observed fluctuations in the distance to the PODF follow a similar pattern for the two velocities. This indicates that the amount of stimulation introduced on the jet is dependent on the resonance frequencies of the nozzle system. It can also be seen in the curves that there are some frequencies between 1.4 and 1.5 MHz where the stimulation is very weak. In order to assure stable drop formation the frequency of stimulation should be selected to a value where the distance to the PODF is short, i.e., where the charging current is low.

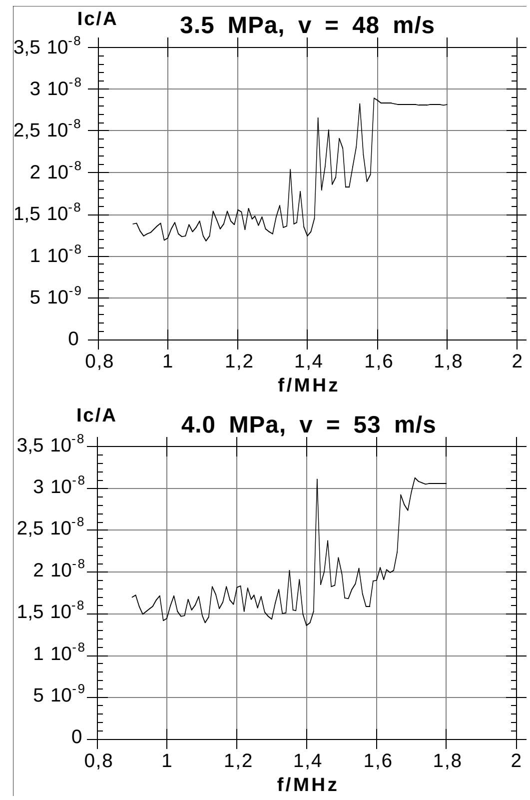

Figure 7. Charging current measured at two jet velocities when the stimulation frequency was varid between 0.9 - 1.8 MHz.

Width of the Forbidden Region

Figure 8 and Figure 9 show the PMP and RMP curves obtained for the stimulation frequencies 0.97 MHz and 1.04 MHz, respectively. The results clearly demonstrate the influence from the satellite drops on the measurements. The two drop frequencies used in the figures are both close to 1 MHz. In the photographs of the drop formation for 0.97 MHz (Figure 8) it can be seen that the satellite drops are not cut off from the main drop until the main drop has been cut off from the continuous part of the jet. The main drop and the satellite are charged simultaneously. The RMP diagram shows that the drops are fully charged over approximately 180 degrees of the drop formation cycle. (The decrease in charging current close to 0 degrees is probably due to drift in the measurement). Thus, the width of the forbidden region in this case is 180 degrees.

For the drop formation frequency of 1.04 MHz (Figure 9), the satellite drop is cut off before the main drop. The main drop and the satellite drop can then be charged individually leading to the shape of the PMP curve. The RMP curve is distorted at around 200 degrees and it can be seen in the photographs that this is the position of the satellite cut-off. For RMP applied at phase values up to 200 degrees the charge is transported by both the satellite drop and the main drop. When the RMP is applied after satellite cut-off, only the main drop is charged. Since the satellite drop will merge backward it is important that both the main drop and the satellite drop are fully charged or discharged to achieve a correct drop flight. This is fulfilled for phase values up to

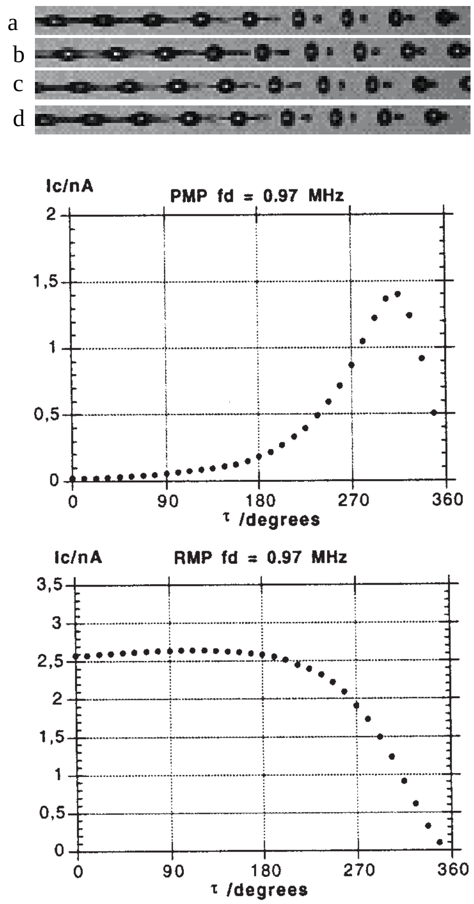

Figure 8. Results from the measurement of the width of the forbidden region for a drop formation frequency of 0.97 MHz. The satellite cut-off occurs after the main drop cut-off. The drop formation is shown above for a) 0, b) 90, c) 180 and d) 270 degrees phase with respect to the main drop cut-off.

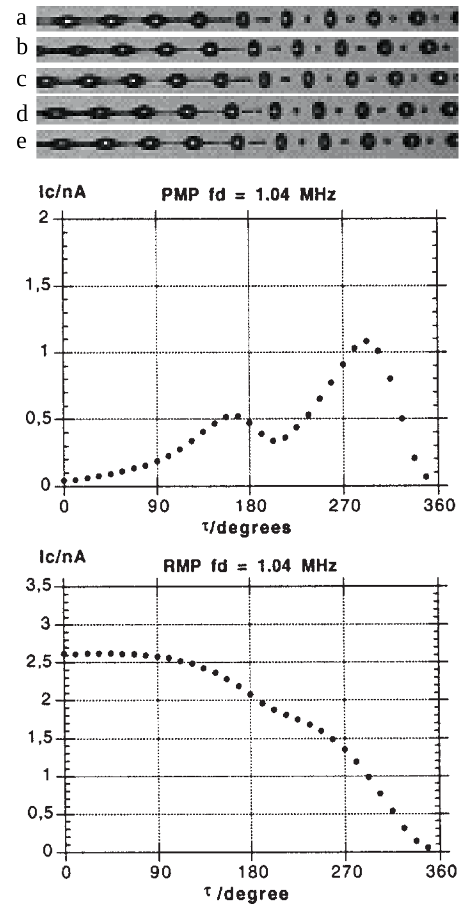

Figure 9. Results from the measurement of the width of the forbidden region for a drop formation frequency of 1.04 MHz. The satellite cut-off occurs before the main drop cut-off. The drop formation is shown above for a) 0, b) 90, c) 180, d) 225 and e) 270 degrees phase with respect to the main drop cut-off.

about 90 degrees and the width of the forbidden region is thus 270 degrees in this case.

The presented methods clearly offer a simple way of evaluating nozzle systems during development and for characterizing the drop formation in order to find the operating conditions for stable drop formation and controlled drop charging.

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