Manipulating Drop Formation in Piezo Acoustic Inkjet

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Abstract

Inkjet developments move towards higher productivity and quality, requiring adjustable small droplet sizes fired at high repetition rates. Normally, maximum jetting efficiency is achieved by tuning the slopes of the driving waveform to the travel times of acoustic waves inside the channel. Important parameters are channel length, compliance of channel cross-section (through its impact on the effective speed of sound in the ink) and the inlet geometry (through its impact on the phase shift of reflected acoustic waves). In addition, nozzle size and drop speed are the main factors determining the default drop size. The shape of the nozzle is important for the acoustic impedance and thus for efficiency and damping (enabling high drop-on-demand frequencies).

In this paper eight drop-size-modulation (DSM) techniques are identified. First, DSM can be achieved by modifying the pulse width and changing the fill-before-fire level. Next, droplet size can be enlarged by using acoustic resonances, either by pre-actuating the meniscus movement or by firing bursts of multiple drops in phase with the channel acoustics. Droplet size can be reduced by using break pulses, especially when combined with a satellite drop formation mechanism. Finally meniscus resonances and drop formation resonances can be used. It is shown that using an appropriate combination of these modulation mechanisms droplet sizes of 7 to 65 pl can be fired at 20 kHz with one printhead geometry.

Introduction

Inkjet is an important technology in document printing and many new industrial applications. Océ applies inkjet in its wide format color printing systems. New inkjet developments move towards higher productivity and quality.

Understanding the drop formation process and all relevant phenomena [1] is the starting point to control the drop formation [2], reduce cross-talk effects and to achieve a maximum reliability, necessary for all productive applications. This paper focuses on the mechanisms involved in firing multiple drop sizes.

Operating Principle

A long ink channel with a nozzle at the right and a large reservoir at the left is the basic geometry of the inkjet device as shown in figure 1. A piezo actuator element drives each channel. To fire a droplet, an electric voltage is applied and the channel cross-section will be deformed by the inverse piezo-electric effect. This results in pressure waves inside the channel. The pressure waves propagate in both directions and will be reflected at changes in characteristic impedances (variations in cross-section and compliance of the channel structure). In the simplified diagram in figure 1 a first slope of the driving waveform enlarges the channel cross-section and the resulting negative pressure wave will be reflected at the reservoir at the left. The reservoir acts as an open end and the acoustic wave returns as a positive pressure wave.

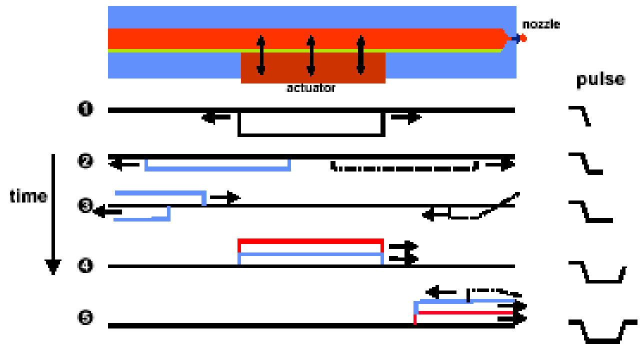

***Figure 1**. Actuation and resulting channel acoustics*

The second slope of the driving waveform will reduce the channel cross-section to its original size and will amplify the positive pressure wave when tuned to the travel time of this acoustic wave. The resulting pressure just before the nozzle is shown in figure 2.

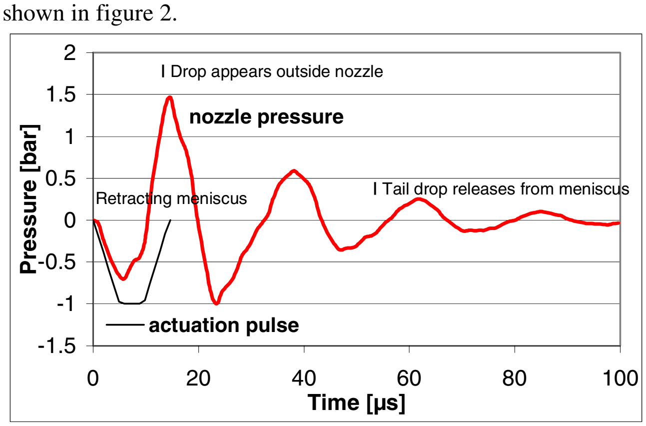

***Figure 2**: With "narrow-gap" model [1] calculated nozzle pressure for an 8 mm channel geometry.*

The channel geometry and driving waveforms are designed to generate a large incoming positive pressure peak at the nozzle which drives the ink through the nozzle. In the small cross-section of the nozzle acceleration of the ink results in drop formation.

Drop Size

The drop size will be equal to the volume of the ink transported outside during the drop formation process. A typical drop formation for an 8 mm long channel is shown in figure 3. After 15-20 μs the head of the drop appears outside the nozzle with a relative high speed. The head of the drop drags a long tail along which slows down the head of the drop to the final drop speed of 5-9 m/s. This tail breaks off after 55-60 µs.

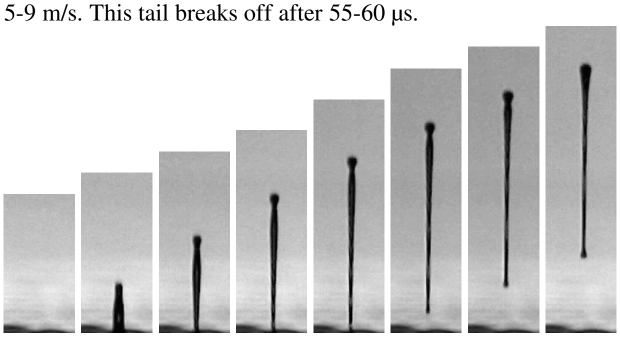

***Figure 3**. Measured drop formation at 10, 20…80 µs after start actuation for an 8 mm channel geometry.*

As a first order approximation of the drop size we take a cylinder as the shape of the ink column transported outside with a volume of nozzle size times length of the cylinder. The length of the cylinder equals the drop speed times drop formation time. Important parameters for the drop formation time are the width of the driving waveform, the travel time of the acoustic wave, the nozzle shape (by its impact on the acoustic impedance) and ink properties as viscosity and surface tension. The travel time of the acoustic wave is given by the channel length, the inlet geometry (because of the phase shift of the reflected wave) and the effective speed of sound inside the channel. The effective speed of sound is given by the speed of sound of the ink itself c_0 and the compliance of the channel cross-section β. The compliance reduces the effective speed of sound as predicted by the "narrow-gap" theory [3] implemented in our acoustic modeling [1]:

$$c_{eff} = \sqrt{\frac{c_0^2}{1+\rho\, c_0^2\, \beta}} \tag{1}$$

Maximum jetting efficiency is achieved by tuning the slopes of the driving waveform at the travel times of the acoustic wave inside the channel. At maximum jetting efficiency all parameters are defined by the printhead geometry and ink properties resulting in a default drop size for that geometry.

Drop Size Modulation

Driving pulse width

By changing the time delay between the two slopes of the simple driving waveform as shown in figure 1, the drop formation time is modulated by the variation of the width of the positive pressure peak. The more damping in the acoustics, the more effect of driving pulse width. Since the timing of the slopes is not tuned to the travel time of the acoustic wave, the pressure wave will be less effectively amplified. This results in higher driving voltages.

In figure 4, the measured drop size at a drop speed of 7 m/s and the relative driving voltage (driving voltage with most efficient pulse width is 100) are shown for an 8 mm channel geometry similar to the geometry shown in figure 1 with nozzles of 36 µm diameter. With a maximum loss in driving voltage of 20 % the drop volume can be changed from 36 to 54 pl. For a 5 mm channel geometry and a nozzle diameter of 24 µm, the drop size can be adjusted between 10 and 16 pl at a drop speed of 6 m/s.

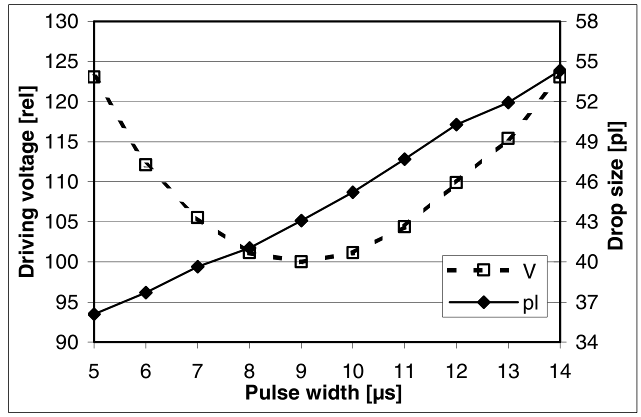

***Figure 4**. Measured driving voltage and drop size with constant drop speed as function of pulse width for an 8 mm channel geometry and 36 µm nozzles.*

Fill-before-fire level

With only two slopes in a driving waveform as described in the previous section, a maximum fill-before-fire action is achieved, also denoted as pull-push action [4]. Variation of the fill-before-fire level requires a third slope in the driving waveform and a two-sided driving amplitude. This can be used for a better control of meniscus movement [5] but also for changing the drop size. With a lower fill-before-fire level the meniscus retraction before firing a drop will be less. Because of the larger amount of ink in the nozzle when the positive pressure peaks reaches the nozzle, drop sizes will be larger. In the 5 mm channel geometry, the drop size range can be extended to 22 pl. This action also requires more driving voltage since now only a part of the first and second slopes will reinforce each other. With no fill-before-fire at all or a push-pull action there is no amplification of the pressure wave and the required driving voltage increases by a factor of two.

Pre-actuation

Pre-actuating the meniscus can be used for conditioning the ink [5], reducing the required driving voltage [6], but also for increasing drop size. An extra amount of ink just before the nozzle must be created with the pre-pulse. This amount of ink will be dragged along with the main drop formation process as shown in figure 5. When the main drop collides with the extra amount of ink before the nozzle, the head of the drop deforms a lot as shown in the insert of figure 5.

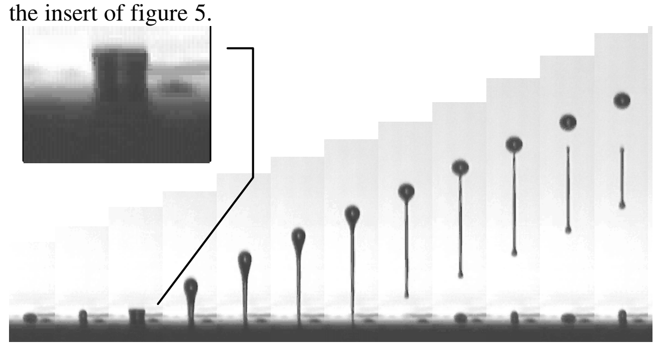

***Figure 5**. Drop formation with pre-actuation after 0,10…110 µs for an 8 mm channel geometry.*

The Weber number (ratio between inertial and surface tension forces) of our drop formation is about 40 and the Reynolds number (ratio between inertial and viscous forces) is about 20. This means that the drops will recover their spherical shape, in our case with drops of 10-30 pl size within a few µs.

With a pre-pulse the required driving voltage for larger drops does not increase but the driving waveform will be longer. A pre-pulse increases the total drop volume up to 10 pl when in phase with the channel resonance.

Bursts of drops

When firing drops at a high repetition rate, the acoustic waves of the preceding drop formation cycle will not come at rest when the next cycle starts. As an example, the variation of the drop speed for an 8 mm channel geometry is shown in figure 6. This cross-talk effect in time results in drop speed variations, which reduce print quality. The cross-talk level is highly affected by the channel length and the nozzle size but also by driving waveform variations. Pulse width other than the most efficient one and a high fill-before-fire level reduce cross-talk in time and pre-actuation in phase with channel acoustics increases cross-talk in time.

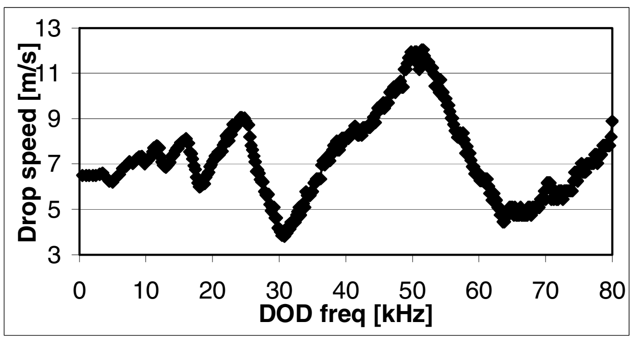

Figure 6. *Measured effect of repetition rate on drop speed for an 8 mm channel geometry.*

When firing the next drop at a timing which corresponds with a maximum in the frequency-speed curve the next drops will move faster and merge with the first drop as shown in figure 7. The driving waveforms will be long with multiple pulses at a timing of 20 µs for an 8 mm and 12.5 µs for a 5 mm channel geometry.

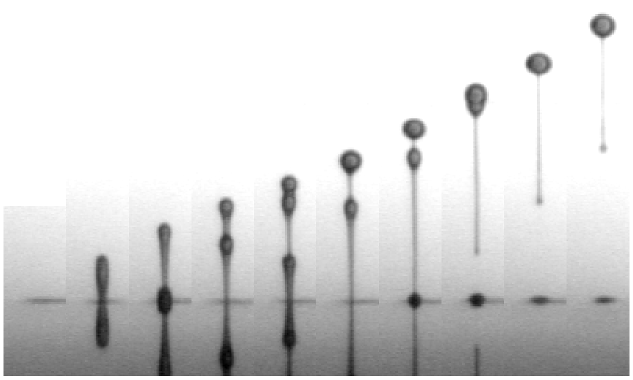

Figure 7. *Drop formation after 10,20….100 µs when firing a burst of three drops for a 5 mm channel geometry.*

We can extend the drop size range for the 5 mm channel geometry to drop sizes of 36, 50 or 65 pl with bursts of 2, 3 or 4 drops. Depending on the maximum drop on demand frequency the number of drops will be limited. With the 5 mm channel geometry four drops can be fired within a burst at a frequency of 20 kHz, at 40 kHz only two.

Break pulses

The opposite of pre-actuation is the use of a break pulse just after the main pulse. This can be a pulse of the same polarity after a half period of the channel resonance or of the opposite sign after a whole period. This damps the residual vibrations [7]. When a break pulse starts when the main part of the drop is leaving the nozzle, several pl of drop volume can be held back. With a break pulse after a half period with an amplitude of 50 % of the main pulse, the smallest drop size with the 5 mm channel geometry can be reduced from 10 to 7 pl. A break pulse reduces cross-talk in time, especially when there is only one dominant frequency in the channel acoustics. A disadvantage of a strong break pulse is that refill of the nozzle will be less. Refill is driven by the variable mass effect and channel acoustics. For more complex situations with more than one important frequency iterative learning control can identify suitable break waveforms [2].

Satellite drop formation

With a maximum fill-before-fire level the meniscus retraction is also at its maximum so there is a minimum amount of ink inside the nozzle. A positive pressure peak will result in a very fast acceleration. The acceleration of the ink has to stay below a critical level. Above this level surface tension forces are no longer capable of holding the amount of ink together. From simulations with the volume of fluid software Flow3D (Flow Science Inc., Santa Fe) we know that in an 8 mm channel design this already occurs at 20 µs after start of the actuation and only at 10 µs after the ink appears outside the nozzle as shown in figure 8. A maximum in speed appears both behind the head of the drop as well at its front, indicating that this part will continue to move away from the head.

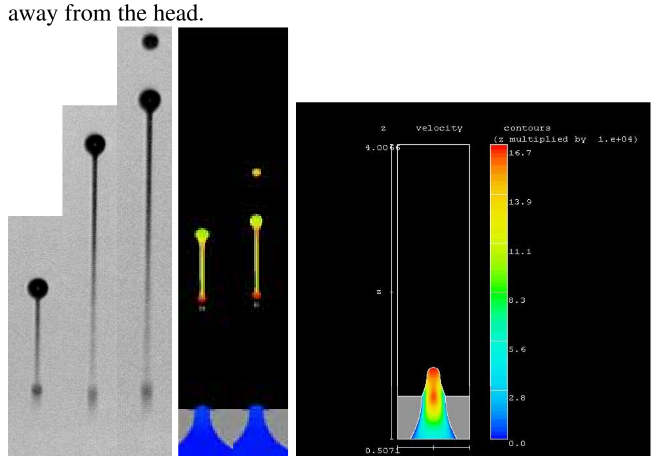

Figure 8: *Satellite drop formation at high drop speed, measurements and Flow3D simulations.*

Not only with the fill-before-fire level buth also with increasing driving pulse width, the meniscus retraction increases and the amplitude of the pressure peak decreases. Both are important for the onset of fast satellites. Nozzle impedance is important because a high impedance gives a high amplitude of the pressure peak which results in more satellite drop formation.

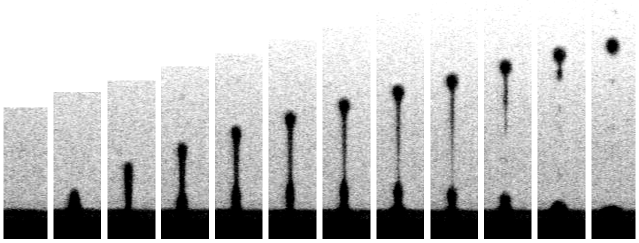

Figure 9*: Drop formation with a split and block pulse after 5,10,15……..60 µs in a 5 mm channel geometry.*

In the 5 mm channel geometry after 10 µs the ink in front of the head cannot be captured anymore when accelerated too fast and we can start with a second pulse that blocks the main drop formation. In figure 9 the drop formation is shown using a driving pulse which results in a supercritical acceleration, followed by a counter pulse which blocks the main drop. The remaining satellite results in a small drop of 7 pl.

Meniscus oscillations

Exciting resonances in the meniscus surface gives a higher order drop formation which results in small drops [8]. In an 8 mm channel geometry the third mode resonance results in 3 pl drops as shown in figure 10. Numerical simulations with Flow3D show the same results.

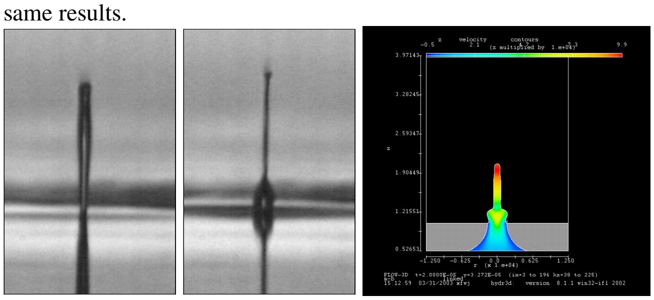

Figure 10*: Measured drop formation in normal first mode and third mode and Flow3D simulation of the third mode.*

The jetting stability is poor however and there are problems with wetting and satellite drop formation. In our printheads only at very low drop speed (below 4 m/s) drop formation remains stable. We need a better understanding of the underlying mechanisms to get more control on this mechanism.

Drop Formation Oscillations

Finally exciting oscillations in the drop formation process is a possibility for firing small droplets from a large nozzle [9]. For this mechanism the Ohnesorge number (ratio between viscous forces on one side and inertial and surface tension forces on the other side) should be of order 0.1 and the time of the slopes of the driving waveform about 0.03 times the capillary time scale, which is about 10 µs in our case. Under these condition an oscillation in the flow inside the nozzle generates small drops.

In the reference a drop size reduction by a factor of 10 was reported for a default drop size of 40 pl. In our printhead geometries the capacitance of the piezo-electric actuator is too high to apply slope lengths of order 0.3 µs and we did no research on the applicability of this mechanism.

Conclusions

In this paper we have identified eight mechanisms for drop size modulation: driving pulse width, fill-before-fire level, pre-actuation, multiple drops, break pulse, satellite drop with split and block pulse, meniscus oscillations and drop formation oscillations. With a selection from these mechanisms we can fire 7-65 pl drops up to a frequency of 20 kHz or 7-50 pl up to 30 kHz using a 5 mm channel geometry with 24 µm nozzles, figure 11.

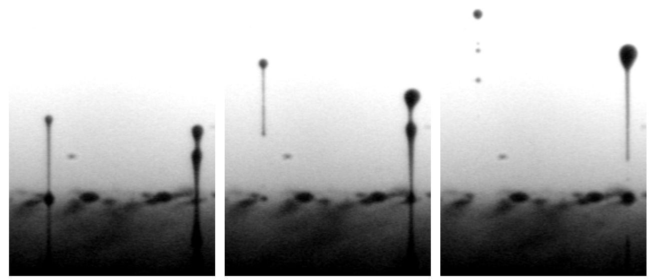

Figure 11*: Firing 7 and 50 pl drops from two neighbourimg channels.*

To extend these ranges to smaller drops we will continue our research to the Faraday oscillations of the meniscus surface and parametric instabilities of the meniscus movement.

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Author Biography

Herman Wijshoff received his M.Sc. degree in Physics from the Eindhoven University of Technology, the Netherlands, in 1986 and joined the Research and Development department of Océ in Venlo. Since 1997 he is involved in the inkjet research program. He focussed primarily on the modeling of the functional behavior of inkjet printheads.