Optimization of a DoD Print Head Signal for the Ink-Jetting of Conductive Circuits

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Abstract

The inkjet-printing principle is becoming more and more important for electronical applications. Printing conductive circuits is possible with colloidal inks so far, but stability of the printing process is not guaranteed at all times.

The piezo activation signal, meaning its shape, strength and duration influences the droplet formation process and printing stability enormously. The droplets' velocity and volume can vary from 1 to 6 m/s and 100 to 300 pL respectively for a 100 µm nozzle print head. Small droplets are desired for highest resolution, but they depend on the piezo activation signal u(t). Furthermore, the stability of the printing process is influenced by the energy provided to the droplet.

By means of a frequency response analysis of the print head, new shapes of u(t) are generated and tested practically. The influences of different piezo signals on the printing process are shown by measuring volume and velocity of the generated stable droplets. The article shows a method of optimizing a piezo activating signal to gain accuracy and resolution for inkjet printed electrical circuits.

Introduction

The Drop on Demand inkjet principle has become more and more important for non-graphical applications in the past years. In the production of electronic devices such as LCD displays [1], OFETs [2] or conductive circuits [3], this technique shows high potential besides conventional photolithography or screen-printing. The advantages of the DoD-method are obvious: No screens are needed and contactless printing on almost any surface topology is possible. Furthermore, the amount of solid conductive substance can be adjusted by variation of the droplets' diameters, the number of deposited layers and the droplet step size in *x*- and *y*-directions. As a result, expensive conductive material can be saved.

This article shows the influences of shape and amplitude of the piezo voltage signal on the droplet generation and especially on the droplets' velocity and volume ranges. Earlier investigations have shown that significantly different nozzle diameters may result in overlapping droplet volume ranges (comparison of droplet volumes generated with nozzles of diameters 50, 70 and 100 µm), dependend on pulse duration and voltage amplitude [4]. In a further step, the influence of the voltage shape is investigated in order to increase the number of printable inks.

The print head's energy run

The piezo DoD print head [5] can be activated by a nearly rectangular voltage pulse with a pulse amplitude between 30 and 250 V and a pulse duration between 5 and 100 µs. In a first step, the rise and fall times of the edges are set to 1 µs. The voltage $u(t)$ and the corresponding piezo current $i(t)$ can be seen in **figure 1** as well as the piezo power $p(t)$ and its energy run $e(t)$. The energy run is calculated as the integral of the piezo power

$$e(t) = \int_0^t u(\tau) \cdot i(\tau)\, \mathrm{d}\tau \qquad (1)$$

and can be seen as the piezo's response to its activation signal $u(t)$. The energy run describes the absorbed (rising part of the voltage signal), released (falling part) and dissipated (turned into heat) portion of energy during one signal period, that means while generating one droplet.

The modification and optimization of the piezo's voltage shape is targeted at the following improvements:

- Increasing the volume and velocity ranges of the droplets for a certain ink,
- adjustment of the voltage shape to inks that need a special signal shape to be printable,
- reduction of the oscillations in $i(t)$ and $e(t)$,
- reduction of the current amplitude to minimize the electric strain on the piezo and
- adaption of the portion of applied energy that is turned into heat in order to optimize heat development.

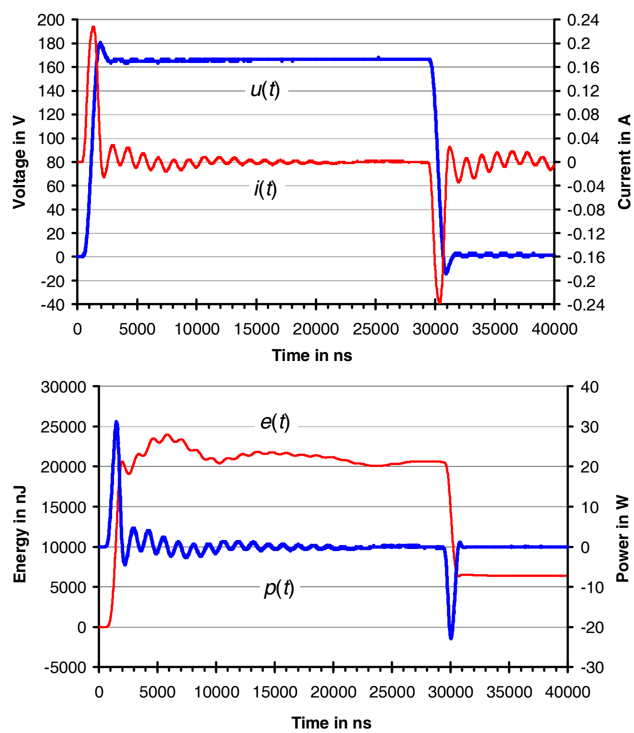

Figure 1*. Ramp piezo voltage signal (1 µs rise time) with current, power and energy run*

Starting from rise and dwell times of 1 µs, these periods are increased to 2, 3 and 4 µs. The overall piezo voltage duration is set to 30 µs and kept constant with variable rise and dwell times as described. Doing this, the current pulses and power peaks are reduced significantly.

The current pulses start with values of 0.23/-0.24 A (rising/dwelling edge) for the 1 µs ramp signal and show a peak of 0.06/-0.06 A for the 4 µs ramp signal. The power peaks decrease from 31/-24 W (1 µs ramp) to a third and amount to 10/-8 W (4 µs ramp) then, which can be seen in **figure 2**. Furthermore, the high-frequency oscillations in the energy run do not occur any longer. Consequently, longer rise and dwell times reduce not only the current and power peaks but also the oscillations in the current and power run.

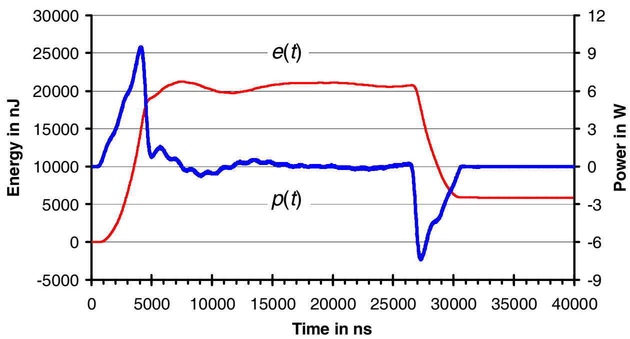

***Figure 2**. Piezo power and energy run for a 4 µs ramp voltage signal*

The portion of energy dissipated by the piezo seems to be independend of the rise and dwell times of the voltage signal. In all four cases, the value of the energy dissipated into heat and mechanical energy is about 6000 nJ. This portion of energy can be reduced by changing the voltage shape from ramp-shape to exponential-shape. By keeping the signal overall time at 30 µs and using exponential rise and dwell developings of 10 µs each, the power and energy runs depicted in **figure 3** can be achieved. In this case, oscillations occur again and power peaks are enlarged by nearly 50 % compared to the 4 µs ramp-shape. However, the dissipated energy is reduced to 4400 nJ.

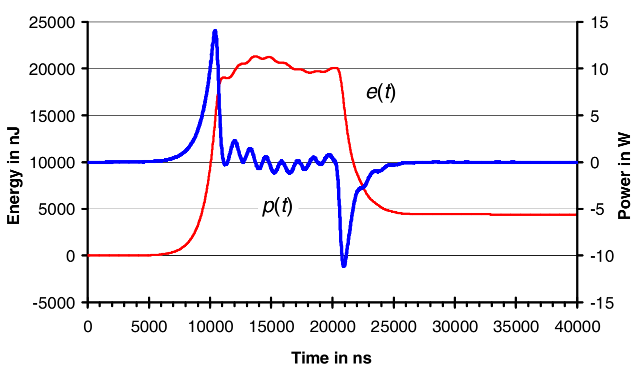

***Figure 3**. Piezo power and energy run for a 10 µs exponential voltage signal*

Table 1 compares the parameter ranges for stable droplet generation of the three signals ramp-shape 1 µs, ramp-shape 4 µs and exponential-shape 10 µs supplemented by a fourth signal, which is a low pass (LP) filtered rectangular pulse. The influence of the signal shape modifications especially on the droplets' volumes and velocities can be seen. So far, it was not possible to completely eliminate the oscillations in the piezo current and thus in the piezo power run (cf. figure 2).

Table 1: Parameter ranges for modified voltage shapes

Ranges	Ramp 1 µs	Ramp 4 µs	Exp 10 µs	LP-filtered
û in V	150 - 230	155 - 220	170 - 240	165 - 250
V in pL	139 - 321	134 - 271	90 - 172	126 - 282
v in m/s	0.6 - 6.1	1.0 - 5.6	0.8 - 5.2	0.9 - 6.3

A reduced oscillation behaviour can be detected for the 4 µs ramp signal, however the high-frequency oscillation partly remains in that case. Optimization goes on for that reason. The measurement of the print head's power amplitude characteristic in a frequency range of a sinusoidal signal between 50 kHz and 500 kHz, as shown in **figure 4**, leads to the development of a low pass filtered rectangular pulse signal with 30 µs pulse duration.

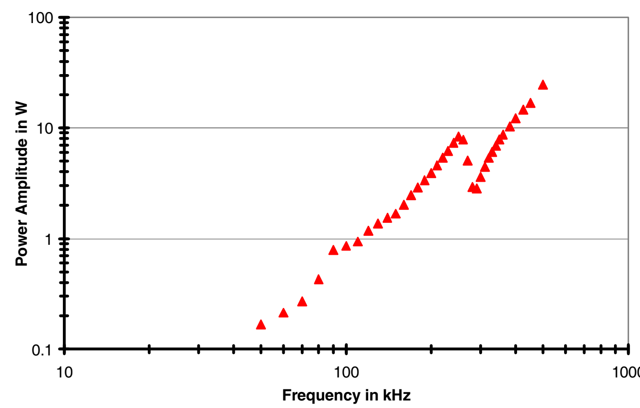

***Figure 4**. Power amplitude characteristic*

This LP-filtered signal only considers frequency components up to 200 kHz for a piezo activation frequency of 1 kHz. The voltage pulse depicted on the left side of **figure 5** is developed into a Fourier series, which yields the voltage shape presented in the right part of figure 5. This LP-filtered signal is characterized by oscillations before the rising edge and after the falling edge and also between the two overshooting peaks.

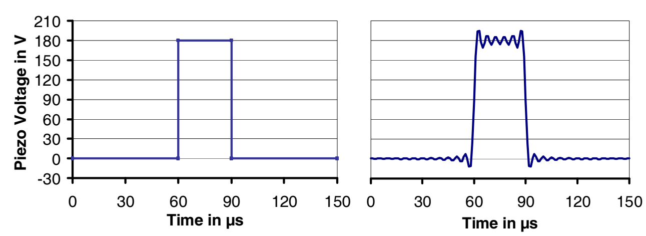

***Figure 5**. Original (left) and LP-filtered (right) rectangular pulse*

For activating the piezo with this LP-filtered signal it is smoothed out between the peaks and at the edges only one oscillation period is considered. The rise and dwell times of this new signal are 4 µs and correspond to the 4 µs ramp signal. The use of this voltage signal shape eliminates the high-frequency oscillations in the piezo current and thus in the power run (see **figure 6**).

The energy curves of the 4 µs ramp and the LP-filtered signal show qualitatively equal runs, but in the time interval [10000 ns; 25000 ns] the value of the energy is 4000 nJ higher for the LP-filtered and smoothed signal at average. The same applies to the dissipated energy. Reason for that is the voltage amplitude, being at 180 V higher than in case of the 4 µs ramp signal (170 V). A higher voltage is chosen to achieve droplets with comparable volumes and velocities. Using an amplitude of 180 V for the LP-filtered signal, the droplets have a volume of 168 pL and a velocity of 1.7 m/s. With 170 V and a 4 µs ramp-shape signal the droplet parameters are 171 pL and 1.8 m/s. Hence, the droplet generation is more inefficient with the LP-filtered signal, a higher voltage is necessary.

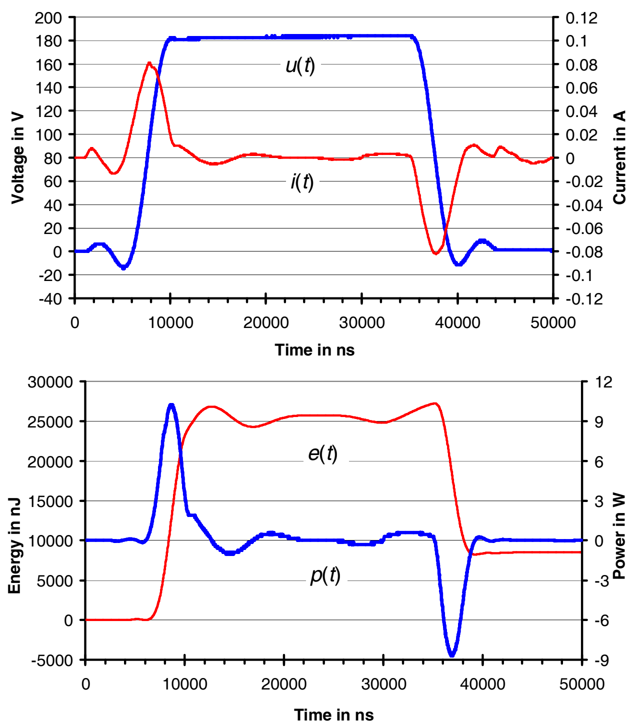

Figure 6. *LP-filtered piezo voltage signal with current, power and energy run*

The droplets' volume and velocity ranges

The consideration of the piezo's power and energy run to reduce the oscillations and the amount of dissipated energy makes sense from the material and energetic point of view, but what is more important for the printing process is the possibility to influence the ranges of the droplet's volume and velocity by activating the piezo with an optimized voltage signal. **Figure 7** shows a droplet image and the system analysis working place where measurements are taken. The detailed volume and velocity ranges according to table 1 are depicted in **figures 8** and **9**. The organic solvent ethylene glycol is used for these measurements because it can be printed very stably, which means the droplets' positions are exactly the same at same observation times. The overlay image of 30 droplets shows sharp edges, therefore measuring the volume and velocity is possible with highest precision [6].

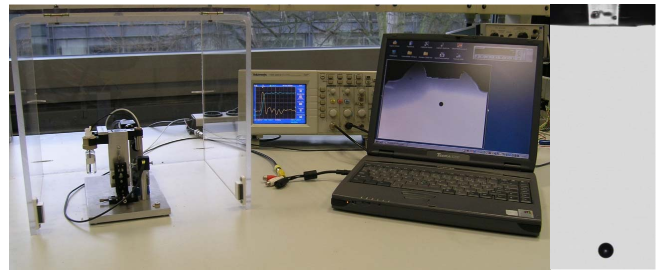

Figure 7. *System analysis working place and droplet image*

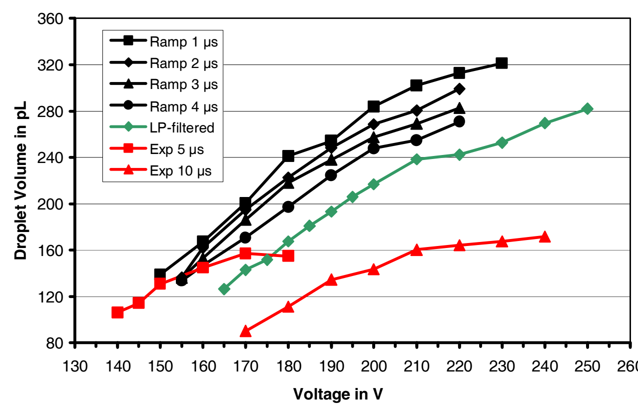

Figure 8. *Droplet volume ranges for varied piezo voltage shapes*

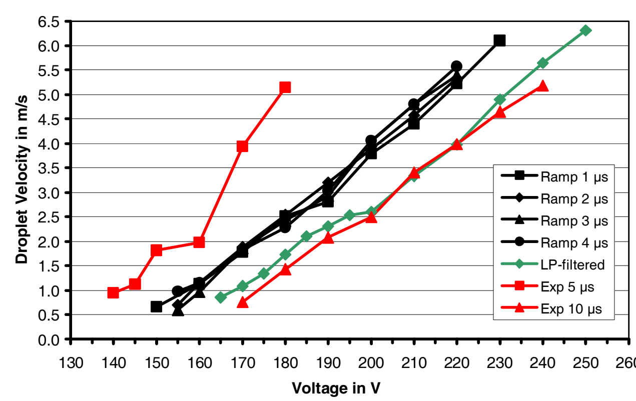

Figure 9. *Droplet velocity ranges for varied piezo voltage shapes*

Examining figure 8 and table 1, three phenomena can be iden-tified: If the duration of the voltage rise time increases (1 µs vs. 4 µs vs. 10 µs) the ranges of achievable droplet volumes decrease. Furthermore, the minimum voltage necessary to start stable printing gets higher and the droplet volumes are smaller for a given voltage of 170 V (200 pL vs. 171 pL vs. 90 pL). Increasing the piezo voltage's rise and dwell times worsens energy insertion into the oscillating liquid in the capillary, so the pressure waves build up less efficiently. A dependency on the shape and length of the pulse edges is given as well, which is confirmed by a reduction of the rise time from exp 10 µs to exp 5 µs (cf. figure 8). The minimum voltage amplitude where droplet generation begins is 140 V for the exp 5 µs signal shape.

The volume curve for the LP-filtered rectangular pulse is a right-shifted version of the volume curve for the 4 µs signal. A higher voltage amplitude is necessary to achieve the same droplet volume when activating the piezo with the smoothed LP-filtered signal. An activation of the piezo by means of the original LP-filtered signal as shown on the right side of figure 5 would shift the volume curve even further to the right. From the practical printing point of view, the LP-filtered signals do not have any advantages, their only benefit is the reduction of oscillations in the current and power runs.

The achievable resolution of printed structures is an essential aspect when building up electronic devices by means of the DoD method. It depends on the droplet size and droplet velocity in the moment of impact on the substrate. Thus, the major advantage of the piezo signal optimization can be evaluated at that very moment. While maintaining a droplet velocity between about 1 m/s and 5.5 m/s for the ramp and exponential signals, the corresponding generated volumes vary enormously (see figures 8 and 9). Consequently, it is possible to produce a droplet with a much smaller volume but the same velocity when using the exponential voltage signal shape. As a result, the resolution on the substrate is better. Especially in the low voltage range (amplitude < 150 V), volumes of less than 130 pL (lower limit for the ramp signals) can be realized with the exp signals.

The solvent ethylene glycol is basis for the presented print results as already mentioned. The medium does not contain any particles, so the repeatability of droplet positions is best allowing for accuracy in the volume and velocity measurements. Colloidal suspensions that contain metal particles are printable with the used print head as well, but oscillations of the droplets' positions make exact measurements of volume and velocity more difficult due to unsharp droplet shapes in the images. If the print medium consists of a concentrated submicron ceramic suspension, a gain in solid substance concentration leads to an increased voltage amplitude necessary to enable stable printing of the ink. The influences on droplet volume and velocity when printing a colloidal ink are investigated by Reis et al. [7].

Conclusion

The successful printing of (colloidal) inks and the performance of a DoD print head do not only depend on the print medium which has to be adjusted to the print head, but to a great extent to the voltage signal to activate the piezo. By varying the rise and dwell times of a nearly rectangular pulse shape in a first step, oscillations in the piezo's current, power and energy run can be reduced. Furthermore, it is possible to minimize the power peak to lower the electric strain on the piezo. High-frequency oscillations in the energy run are eliminated completely if a low pass filtered voltage signal is set to activate the piezo. When changing the shapes of the rising and dwelling edges of the signal from linear to exponential, the portion of dissipated energy can be diminished.

In a second step, the influence of the voltage shape on the droplets' volume and velocity ranges is shown. Ramp signals with rise and dwell times of 1, 2, 3 and 4 µs enable droplet speeds between 1 and 6 m/s with volumes between 140 and 320 pL. The change to an exponential rise and dwell shape allows for a reduction of the droplet's volume to a range 90 to 170 pL by keeping the velocity nearly constant. Thus, a better resolution on the substrate is possible when building up conductive circuits by means of the DoD method.

As a next step, conductive lines and passive elements are printed with a colloidal silver particle ink to verify the effects of the signal modifications presented in this article.

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Author Biography

Dominik Cibis studied "Cybernetic Engineering" at the University of Stuttgart. His major field of study was "manned spaceflight" with former astronaut Prof. Ernst Messerschmid being his tutor in his diploma thesis. Mr Cibis helped in the "FIPEX on ISS" team developing an oxygen sensor located on the European COF-module of the ISS.

2004 he joined the Institute of Automation Technology in Hamburg/Germany. There he started building up a Drop-on-Demand laboratory together with Prof. Krüger and is engaged in the project "printing of functional materials with inkjet technology".