Model-Free Optimization Based Feedforward Control for an Inkjet Printhead

M. Ezzeldin, P.P.J. van den Bosch, A. Jokic and R. Waarsing

***Abstract*— Inkjet is an important technology in document printing and many new industrial applications. As inkjet developments are moving towards higher productivity and quality, it is required to achieve small droplet size which is fired at a high jetting frequency. Inkjet printers are now widely used to form conductive traces for circuits, as well as color filters in LCD and plasma displays, what makes the printing quality an important issue. In this paper, an optimization-based feedforward control is proposed to improve the printing quality of the piezoelectric inkjet printer. A novel optimized input pulse is proposed and a model-free optimization is applied to obtain the optimal parameters of the proposed pulse. The proposed optimal pulse is applied to the inkjet printhead and the system performance is investigated.**

I. INTRODUCTION

Inkjet printers are non-impact printers that print text and images by spraying tiny droplets of liquid ink onto a medium (paper). Besides the well-known small inkjet printers for home and office, there is a market for professional inkjet printers. All different inkjet applications have their own performance requirements. For professional printing applications, accuracy in terms of microseconds, micrometers and picoliters is desired. It is expected that for future applications these criteria will become even tighter. Here, main targets are a high resolution, a constant quality and a high print speed. These demands can directly be translated into small droplets with constant properties and high jetting frequencies of the printhead.

Currently, most inkjet printers use either thermal inkjet or piezoelectric inkjet technology. A thermal inkjet printer uses a heating element to heat liquid ink to form vapor bubbles, which forces the ink droplets to leave the nozzle. Most commercial and industrial inkjet printers use a piezoelectric actuator in an ink-filled chamber behind each nozzle instead of a heating element. When a voltage is applied, the piezoelectric material changes its shape or size, which generates a pressure pulse in the fluid forcing a droplet of ink to leave the nozzle. This is, essentially, the same mechanism as the thermal inkjet but it generates the pressure pulse using a different physical principle. A piezoelectric inkjet allows a wider variety of inks than a thermal one but the printheads are more expensive. Nowadays inkjet developments are moving towards higher productivity and quality, requiring adjustable small droplet sizes fired at high repetition rates.

In this paper, the piezoelectric inkjet printer is considered. The main goal is to improve the printing quality of the printhead by controlling and keeping both the speed and volume of the ink drop constant at different jetting frequencies.

Optimization of process performance is a natural choice for reducing production costs, improving product quality, and meeting safety requirements and environmental regulations. Process optimization is typically based on a process model that is used by a numerical procedure for computing the optimal solution. However, in practical situations it is difficult to find an accurate process model with affordable effort. Uncertainty results primarily from trying to fit a model of limited complexity to a complex process system (see e.g.[1] and [2]). The model-fitting task is further complicated by the fact that process data are usually noisy and signals often do not carry sufficient information for efficient process identification [3]. Therefore, optimization using an inaccurate model might result in suboptimal operation or, worse, infeasible operation when constraints are present.

A lot of efforts have been already done to produce a good model for the ink channel [4], [5], however, this model is still rather incomplete. In this paper, an optimization-based model-free controller is proposed to improve the performance of the printhead. The model has been replaced by measurements and the optimization problem is formulated to minimize the error between the desired drop speed and the measured drop speed.

The remainder of the paper is organized as follows. First, a system description is presented in Section II. Then, the problem statement is discussed in Section III. Section IV presents the proposed optimization-based model-free controller design. Experimental results are given in Section V. Finally, concluding remarks are collected in Section VI.

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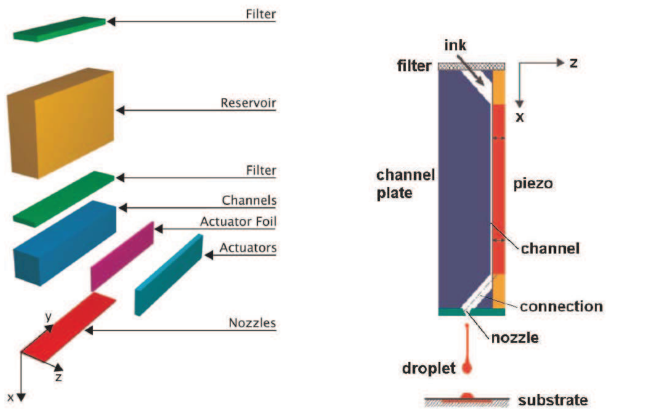

Fig. 1. Exploded view of a piezoelectric inkjet printhead (left) and schematic representation of a single channel (right).

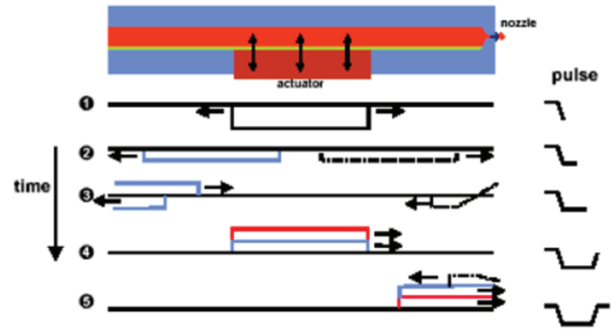

Fig. 2. Drop jetting mechanism

II. System Description

In this paper, we consider a piezoelectric inkjet printhead which comprises two arrays of ink channels with a high integration density. Each channel is equipped with its own piezo-actuator and the printhead works according to the Droplet-on-Demand (DoD) principle. In Fig. 1, an exploded view of the piezoelectric inkjet printhead is shown, together with a schematic representation of a single channel. To fire a droplet, a trapezoidal pulse is provided to the piezo-actuator as shown in Fig. 2. Then, ideally, the following occurs, see e.g. [6] and [7]. First, a negative pressure wave is generated in the channel by enlarging the volume in the channel. This pressure wave splits up and propagates in both directions. These pressure waves are reflected at the reservoir that acts as an open end and at the nozzle that acts as a closed end. Note that the negative pressure wave reflecting at the nozzle causes the meniscus to retract. Next, by decreasing the channel's volume to its original value, a positive pressure wave is superimposed on the reflected waves exactly when they are located in the middle of the channel. Consequently, the wave traveling towards the reservoir is canceled, whereas the wave traveling towards the nozzle is amplified such that it is large enough to result in a droplet.

For most designs, the input pulse is manually shaped based on physical insight into the working of a printhead. For the design presented here, the actuation pulse is tuned to the first eigenfrequency of the ink channel. Additionally, somewhat more complex waveforms are designed for purposes like smaller droplets and constant drop speed. For a piezoelectric printhead, an important set of requirements is related to the resulting drop properties:

- *Drop speed*: The resulting droplets are required to have a certain speed, typically around several m/s.
- *Drop volume*: Depending on the application under consideration, the performance requirement concerning volume typically varies from 5 to 15 picoliters. Smaller drop volumes are for example required with the manufacturing of PolyLEDs. The smallest drop volumes are around 2 to 3 picoliters. For some applications, it is required that the drop-size can be varied during operation. For example, for large areas that need to be covered large drops are desired, whereas for high resolution printing small drops are desirable. This is referred to as drop-size modulation.
- *Drop speed and volume consistency*: The variations in drop volume and drop speed between successive drops and between the nozzles must stay within a certain range, to avoid irregularities in the printed object. In this paper, only drop-to-drop consistency is considered.
- *Productivity*: The productivity of a printhead is mainly determined by the jetting frequency, defined as the number of drops that a channel jets within a certain time, and the number of nozzles per inch (npi-ratio). These two parameters are highly dependent on the specific design of printhead.
- *Reliability*: Reliability of the jetting process is one of the most important performance requirements for printheads. In this context, reliability is defined as the absence of nozzle failure per a certain number of jetted drops, e.g. one failure per one million jetted drops.

III. Problem Statement

Meeting the above described performance requirements is severely hampered by several operational issues that are associated with the design and operation of printheads. Major issues that are generally encountered are residual vibrations and cross-talk.

After a drop is jetted the fluid mechanics within an ink channel are not at rest immediately, apparently traveling pressure waves are still present. In Fig. 3, the system response to a standard actuation pulse is depicted. Also, the time instant of drop ejection is indicated (around 20 μsec in Fig. 3). Usually, the fixed actuation pulse is designed under the assumption that a channel is at rest, which is clearly not true for about 100 to 150 μsec (see Fig.3). This limits the maximally attainable jetting frequency, having significant consequences concerning the productivity and drop consistency of a printhead. If the presence of residual vibrations is ignored and the jetting frequency is increased nonetheless, drop properties start varying. As an example, the so-called Droplet-on-Demand (DoD) speed curve is depicted in Fig. 4, showing the dependency of the drop speed on the jetting or DoD frequency. As shown, considerable speed fluctuations result.

A second phenomenon that is encountered during jetting is the interaction between different channels, called cross-talk. The cross-talk originates from the fact that the pressure waves within one channel influence the neighboring channels. This type of cross-talk is called acoustic cross-talk. Another source of the cross-talk is the deformation of a channel itself. Since all piezo-fingers are connected to a substrate, a deformation of one piezo-unit induces a deformation of the neighboring units. As a result, the volume of the neighboring channels changes too, which induces pressure waves in those channels. The deformation of the printhead structure can originate from two sources. The first one is the result of a channel being actuated and is referred to as direct voltage cross-talk. The second one is the result of the occurring pressure wave that causes deformation of the channel and is called indirect or pressure cross-talk. Fig. 5 shows the influence on the droplet speed of the center channel of an array of 21 channels when neighboring channels are active. As shown in the figure when the direct neighbor (channel 1 or -1) becomes active, a deviation of droplet speed of channel 0 occurred. It can be observed that for channels which are located further away, the influence of cross-talk decreases. Furthermore, Fig. 5 indicates the influence of the cross-talk when a different time delay between the actuation of channel 0 and its neighbors is introduced.

Residual vibration and cross-talk result in a high variation in the drop speed and volume. In the current inkjet printers, a fixed actuation pulse is used, which neglects the above mentioned problems. Fig. 6 shows the jetting 5 drops from one nozzle at different DoD frequencies. It is clear that the drops have different speeds, which affect the printing quality. Our main objective in this paper is to improve the printing quality of the printhead by keeping both the speed and volume of the ink drop constant. So, we want to minimize the speed and volume variations that occur due to the presence of the residual vibration and cross-talk.

The problem statement can be translated to the following objectives:

1) Reducing the speed variations for each nozzle at each jetting frequency.
2) Reducing the speed variations over all the jetting frequencies (flat DoD curve).

In this paper, a new input pulse is proposed, see Fig.7, to reduce the drop speed variations for one nozzle. The cross-talk effect is not considered in the pulse design. A model-free-optimization approach is proposed to obtain the optimal parameters of the proposed pulse.

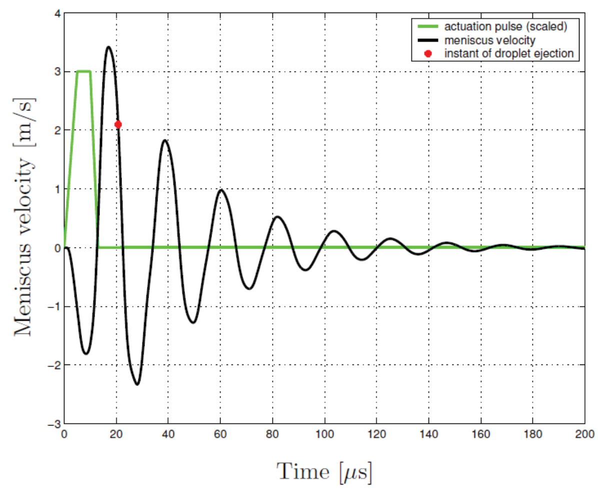

Fig. 3. System response for the standard pulse

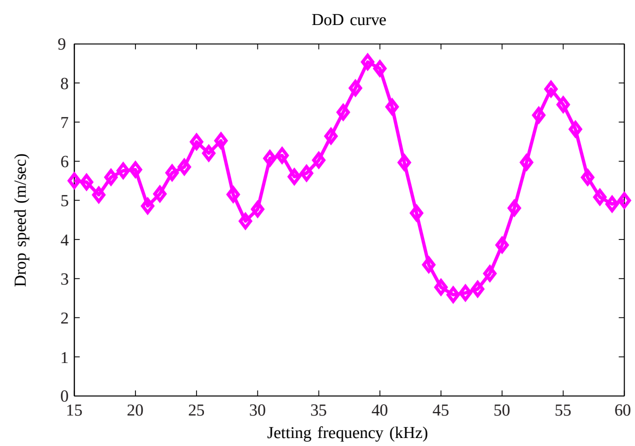

Fig. 4. DoD curve

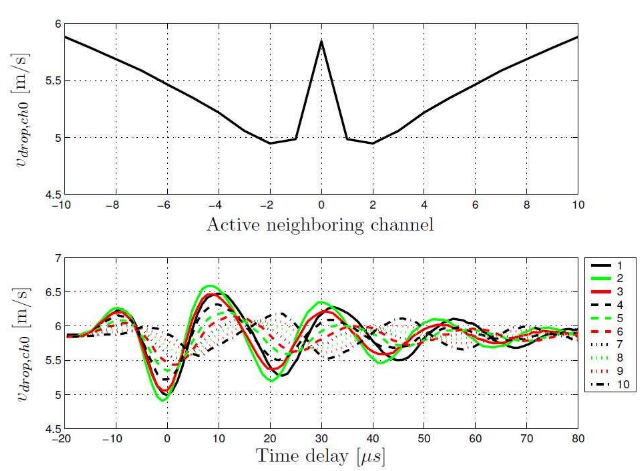

Fig. 5. Influence on the droplet speed of channel 0 (center channel) by actuation of different neighboring channels at the same time (upper plot) and with a varying time delay between the channels (bottom plot).

IV. Optimization Procedure

Feedback control is based on our ability to measure or estimate the controlled variable. In the inkjet printer, there are no sensors for online measurement for the system variables; hence a feedforward controller is the most appropriate solution. Although residual vibration and cross-talk effects are large, they are lightly predictable and reproducible. Hence, a model based feedforward controller can be appropriate for this case. Given accurate knowledge of the plant parameters, it seems straightforward to construct feedforward controller as the inverse dynamics of the plant. This is the Perfect Tracking Controller (PTC) strategy. A lot of efforts have been done to produce a good model for the ink channel, however this model is still incomplete. Moreover, the model of the jetting process is only partly known.

In this paper, we propose a new input pulse. As shown in Fig.7, the new pulse consists of two pulses: an actuation pulse and quenching pulse. The actuation part is used to formulate and jet the drop while the quenching part is used to dampen the residual vibrations. The optimal pulse parameters are calculated by minimizing the error between the actual drop speed and a desired drop speed. In this approach the optimization is carried out on the real set-up instead of using a printhead model. A schematic diagram of the proposed approach is depicted in Fig.8.

A high speed camera is used to record the time history of the drops traveling from the nozzle plate to the paper. An image processing technique is developed to retrieve the actual speed of each drop. First, the image is filtered to get rid of the dots which represent satellites and keep only the droplets dots. Then, the image is converted into a binary image which stores an image as a matrix but can only color a pixel black or white (and nothing in between). It assigns a 0 for black and a 1 for white. After that, a pattern recognition technique is applied to obtain the positions of each droplet and finally the speed of each droplet is calculated based on the droplet position and the traveling time.
An optimization technique is used to get the optimal actuation pulse parameters by minimizing the error between the actual drop speed and a desired reference drop speed. The optimization problem is defined as follows.
The pulse parameters are (see Fig. 7)

$\theta = [T_r \; T_A \; T_f \; V_A \; T_{d_Q} \; T_{r_Q} \; T_Q \; T_{f_Q} \; V_Q]$ with
T_r: The actuation pulse rise time [μsec],
T_A: The actuation time [μsec],
T_f: The actuation pulse fall time [μsec],
V_A: The actuation pulse amplitude [$Volt$],
T_{d_Q}: The time delay between the actuation and quenching pulses [μsec],
T_{r_Q}: The quenching pulse rise time [$\mu sec.$],
T_Q: The quenching time [μsec],

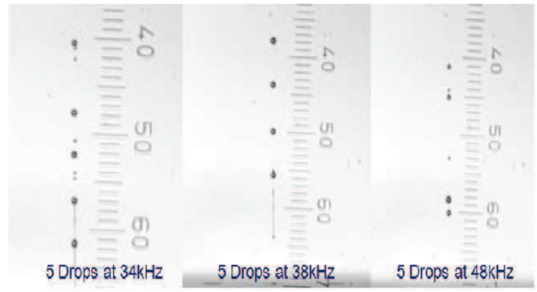

Fig. 6. Jetting 5 drops at different DoD frequencies.

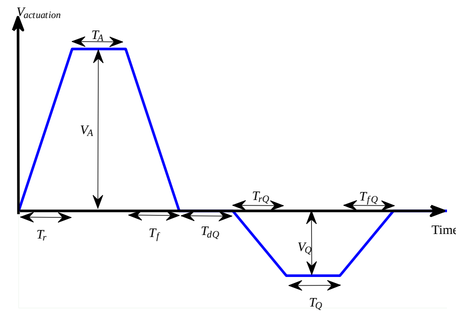

Fig. 7. New input pulse.

T_{f_Q}: The quenching pulse fall time [μsec],
V_Q: The quenching pulse amplitude [$Volt$],

while the optimization cost function is

$$\mathscr{J} = \sum_{f=F_{min}}^{f=F_{max}} \sum_{t=0}^{t=T} (v_{desired} - v_{actual}(t,f))^2, \quad (1)$$
$$\text{s.t.} \quad \theta_{min} \leq \theta \leq \theta_{max}$$

where f is the jetting frequency, $v_{desired}$ is the desired drop speed, v_{actual} is the actual drop speed, T denotes the total time of the experiment and t is the time instances when the measurements are taken.
The optimal pulse which minimizes the cost function is given by:

$$\theta_{opt} = \arg \min_{\theta} \mathscr{J} \quad (2)$$

This problem formulation leads to a nonlinear optimization problem which can be solved by nonlinear optimization techniques. The optimization toolbox in Matlab is used to solve this problem. The *fmincon* function is used, which attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. This is generally referred to as constrained nonlinear optimization or nonlinear programming. To avoid trapping in local minima, the optimization problem is carried out several times using different initial values.

A. *Experimental set-up*

A schematic overview of the experimental set-up is depicted in Fig. 9. With this set-up, inkjet printheads can be

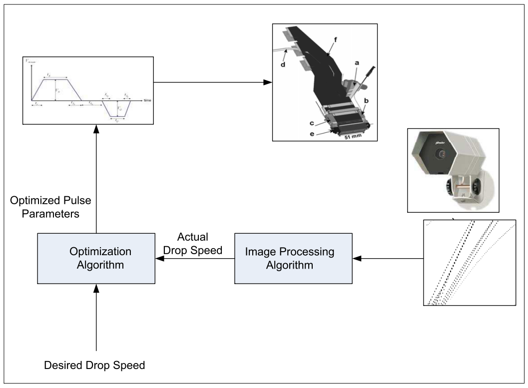

Fig. 8. Model-free optimization feedforward control approach.

investigated in various ways. The only actuator is the piezo-unit of the inkjet printhead. Two sensors are available in this set-up:

i) The piezo-unit not only can be used as actuator but also as sensor to measure the pressure waves in the channel after jetting a droplet.
ii) A Charge-Couple Device (CCD) camera,equipped with a microscope, which is used to monitor the properties of the resulting droplet

A stroboscope provides a short light flash at a defined instant after the droplet is jetted and an image is obtained with a snapshot at a droplet. Both the time duration and the distance that the droplet has traveled are known. By using this information, an estimate of the droplet speed can be obtained. Moreover, it is possible to estimate the volume of the droplet, because the droplet diameter can be determined. Other information which can be obtained concern the droplet's angle, the formation of satellites and the stability of the jet process.

As depicted in Fig. 9, the set-up is connected to a personal computer that is equipped with cards for image processing and communication. On the computer, the desired actuation signals can be programmed and relevant data can be stored and processed. After defining the actuation signal, it is sent to a waveform generator. The waveform generator sends the signal to an amplifier unit, which has a certain gain. From the amplifier unit, the signal is fed to a so-called switch-board. The switch-board is controlled by the personal computer and determines which channels are provided with the appropriate actuation signals. For the tracing of both the actuation and various sensor signals, an oscilloscope is used. This oscilloscope is connected to the computer and displayed data can be downloaded to the personal computer.

V. Experimental results

In this section, the proposed pulse is applied to a real printhead and the results are compared with a standard pulse. Different tests have been carried out to evaluate the efficiency of the proposed pulse. Fig. 10 shows the DoD curve for the proposed pulse and the standard pulse. The

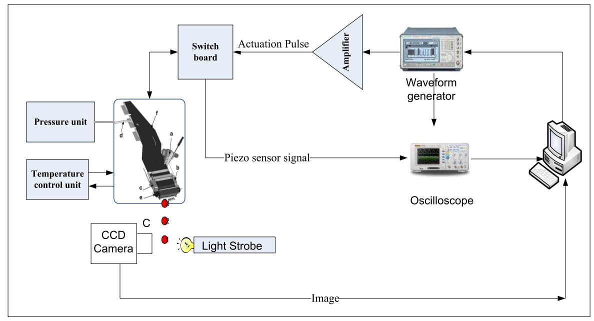

Fig. 9. Experimental set-up.

DoD curve is the steady state speed of the drop at different jetting frequencies. It can be observed that the drop speed variation for the proposed pulse is less than 1.5 m/sec compared with 6 m/sec in case of the standard pulse. The proposed pulse can be used for jetting drops with a DoD frequency up to 56 kHz without overlapping of the pulse. Note that the sudden change in the DoD curve at 56 kHz is due to that the waveform generator can not overlap the pulses.

The second test is jetting 10 drops at different jetting frequencies and analyzing the time history of the drop traveling form the nozzle plate to the paper. Figures 11-12 show the time history of the 10 drops for both the proposed and standard pulses at jetting frequencies 28 and 46 kHz respectively. The time history for the standard pulse shows that the first drop is faster than the subsequent drops. On the other hand, using the proposed pulse shows that the drop speed of the 10 drops are almost the same. The drop speed of the 10 drops over jetting frequencies 20-70 kHz is depicted in Fig.13.

The maximum drop speed variation at each jetting frequency is calculated as

$$\Delta v(f) = v_{max}(f) - v_{min}(f) \tag{3}$$

The maximum drop speed variation is less than 1 m/sec for the proposed pulse while it is 2.5 m/sec for the standard pulse. Fig. 14 shows the drop speed variations for the proposed and standard pulses.

VI. Conclusions

A new pulse has been proposed to improve the performance of the inkjet printhead. A model-free optimization has been used to obtain the optimal parameters of the proposed pulse. The three most prominent performance criteria for a inkjet printhead are its productivity, drop-consistency, and stability. The focus of the research presented in this paper lies on the former two. The attainable performance with respect to these two issues is limited by two commonly encountered operational issues: residual vibrations and cross-talk. In this paper, it has been demonstrated that feedforward control is a suitable control strategy to overcome the residual vibrations and hence increase the performance of inkjet printheads

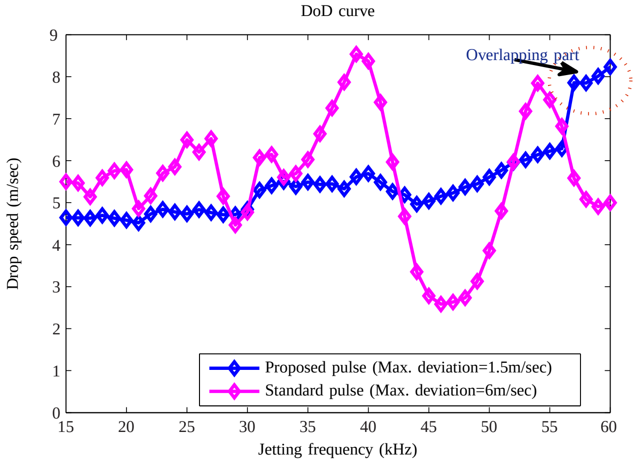

Fig. 10. Optimized DoD curve.

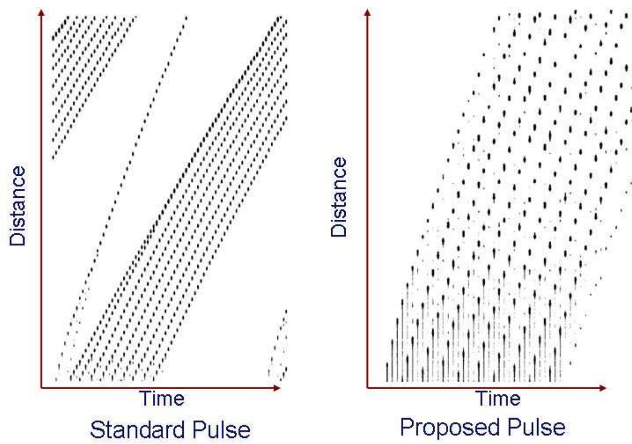

Fig. 11. Jetting 10 drops at DoD frequency 28 kHz.

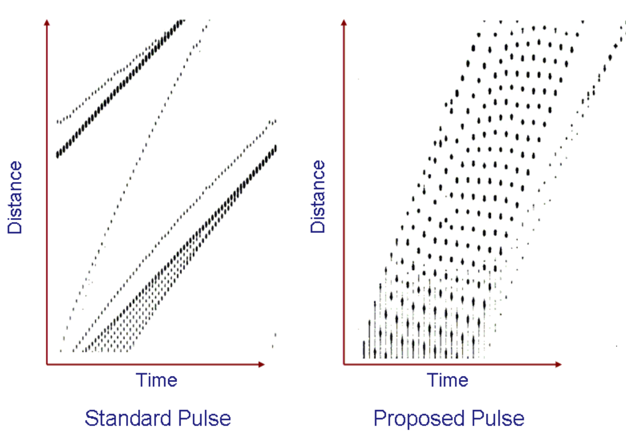

Fig. 12. Jetting 10 drops at DoD frequency 46 kHz.

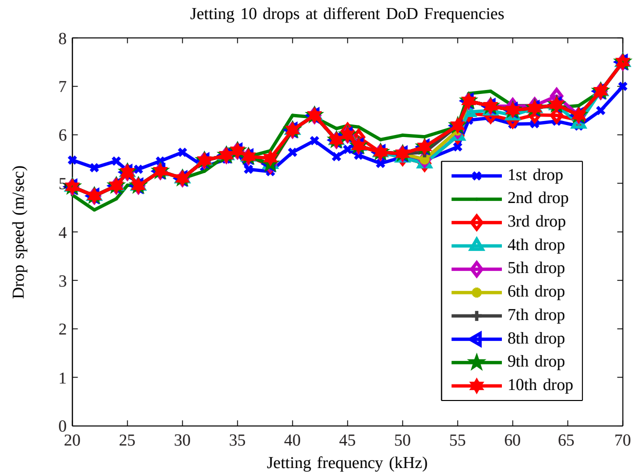

Fig. 13. Jetting 10 drops at different DoD frequencies (20-70 kHz).

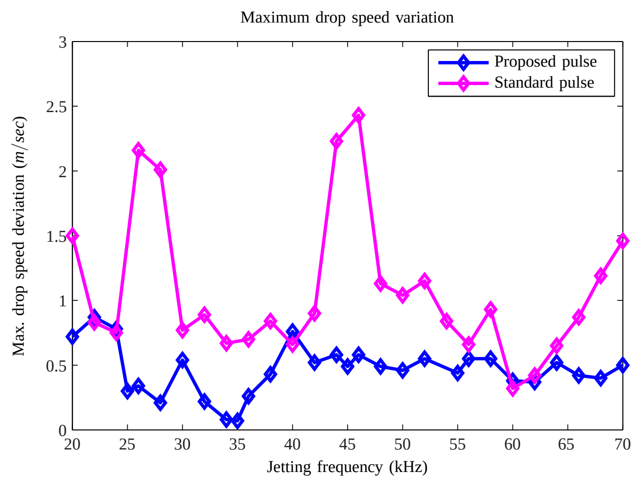

Fig. 14. Maximum drop speed variation at different DoD frequencies (20-70 kHz).

considerably beyond current limits. The experimental results have shown the efficiency of the proposed pulse.

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