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Improving the Performance of an Inkjet Printhead using Model Predictive Control ⋆

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Abstract: Inkjet printing is considered one of the most promising printing technologies that offers several advantages including high speed, quiet operation and compatibility with a variety of substrates. That makes it an important manufacturing technology serving a wide variety of markets. Though the performance criteria imposed by today's applications are quite tight already, the future performance requirements will be even more challenging. However, the attainable performance is limited by two operational issues that are generally encountered, namely residual vibrations and cross-talk. This paper presents an approach based on Model Predictive Control (MPC) with which an input waveform is designed to improve the printing quality of a piezoelectric inkjet printer. The narrow-gap model is employed to predict the response of the ink channel under the application of the piezo input. Simulation and experimental results are presented to investigate the performance of the proposed approach.

1. INTRODUCTION

With rapid advances in information technology (IT), coating and printing processes that mark fine and clear patterns on the substrate are getting more attention. The drop-on-demand (DoD) inkjet printing technology, for example, is now being recognized as a promising tool in this area. It is because the inkjet printing has the advantage of making patterns without any additional lithographic processes. Inkjet printing can reduce the number of processing steps compared with conventional patterning processes, and it finally results in a lower production cost in manufacturing. For this reason, many approaches to substitute the conventional coating method with inkjet printing are in progress. Examples include color filter coating in flat panel display (FPD), electric wire coating on printed circuit board (PCB), UV-curable resins for the fabrication of micro-optical parts, polymer light emitting diode (PLED) displays and etc (Kwon et al. (2005), Bale et al. (2007), Gohda et al. (2006), Koo et al. (2006), Creagh et al. (2004) and Albertalli (2005)).

Drop-on-demand printing includes both *bubble-jet* and *piezoelectric* printers, which are widely used in homes and offices. Both consist of an array of chambers, each of which is linked to an individual nozzle. An electrical signal sent to an actuator then generates a pressure pulse that ejects a droplet of ink onto the substrate. In the case of bubble-jet printers, tiny resistive heaters are used to create small bubbles of steam inside the ink, which is usually water based. As these bubbles expand, they produce the pressure pulse that is needed to eject the ink droplet. The bubble then collapses, the pressure falls, and fresh ink is sucked in from a reservoir. This mechanism is ideal for simple and small devices.

Piezoelectric inkjet printers, in contrast, use a class of ceramics based on lead zirconium titanate. These materials can be processed so that they change shape slightly if subjected to an electric field. When incorporated into an ink chamber, the ceramics apply a pressure to the fluid, which causes the ink to be expelled. Piezoelectric printer mechanisms cost more than bubble-jet systems, but they can use a wider range of inks and can eject far more drops before they fail. The main reason for this is that the ink in a piezoelectric-based printer does not heat up, which means that no steam or other vapor is created that might disrupt the chemistry of the ink. The ink can therefore include highly volatile solvents, which allows companies to try different inks for novel applications. Of particular interest are smart, or functional inks, which consist of a core substance that will perform some electrical, chemical, optical or mechanical function when deposited onto a substrate. By dissolving this substance in the appropriate solvent, the fluid can then be passed through an inkjet printer.

Nowadays inkjet developments are moving towards higher productivity and quality, requiring adjustable small droplet sizes fired at high jetting frequencies. Meeting these 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 (see Section 3). After firing an ink drop, for a certain time pressure waves exist in the ink channel. These disturbances will affect the volume and the velocity of the next drop being fired. The interaction of the wave-like nature of these pressure disturbances, and a constant jetting frequency can result in both amplification of the action pressure as well as in damping. Therefore, the velocity and volume of ink drops depend on the history and the jetting frequency

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of the printhead.

Process industry is characterized by product quality specifications which become more and more tight, increasing productivity demands, new environmental regulations and fast changes in the economical market. In the last decades Model Predictive Control (MPC), also referred to as Model Based Predictive Control (MBPC), Receding Horizon Control (RHC) and Moving Horizon Control (MHC), has shown to be able to respond in an effective way to these demands in many practical process control applications and is therefore widely accepted in process industry. MPC is more of a methodology than a single technique. The difference in the various methods is mainly the way the problem is translated into a mathematical formulation, so that the problem becomes solvable in real time operation.
In this paper, we propose a MPC to design the input actuation pulse for the piezoelectric inkjet printer to reduce the interactions between the jetted droplets taking into account the known jetting bitmap.
The remainder of the paper is organized as follows. First, a system description is presented in Section 2. Then, the problem statement is discussed in Section 3. Section 4 presents the model predictive control design. Simulation and experimental results are given in Section 5. Finally, concluding remarks are collected in Section 6.

2. 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 detailed view of the piezoelectric inkjet printhead is shown, together with a schematic representation of a single channel. To fire a droplet, a trapezoidal voltage pulse is provided to the piezo-actuator as shown in Fig. 2. Then, ideally, the following occurs, see e.g. Bogy and Talke (1984) and Antohe and Wallace (2002). 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, see Fig. 2. These pressure waves are reflected at the reservoir that acts as an open end and at the nozzle that acts as a closed end. 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 at the moment that the reflected pressure wave is located at the position of the actuator (in 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 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. 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 the printhead.

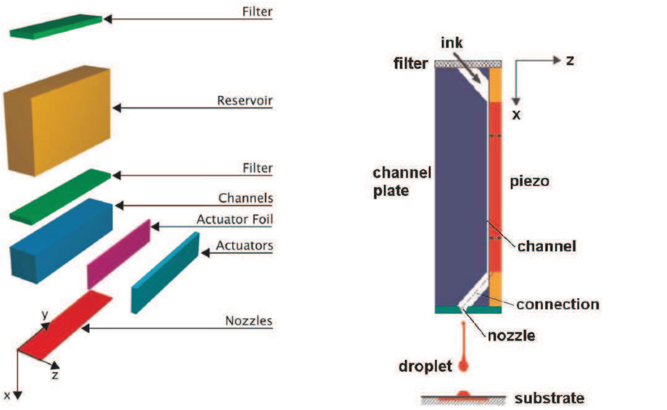

Fig. 1. Exploded view of a piezoelectric inkjet printhead (left) and schematic representation of a single channel (right).

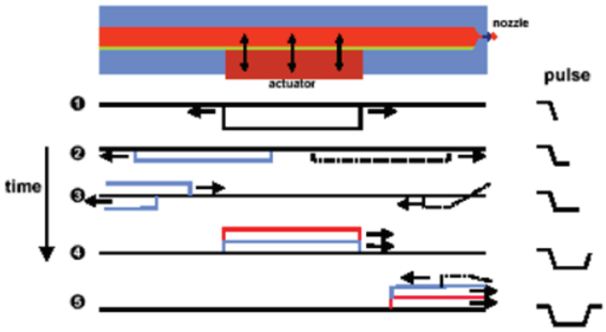

Fig. 2. Drop jetting mechanism

3. PROBLEM STATEMENT

Meeting the above described performance requirements is severely hampered by several operational issues that are associated with the design and operation of printhead. 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. Traveling pressure waves remain 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, and has 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.
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 the channel. 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 the 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*.

Residual vibration and cross-talk result in high variations in the drop speed and volume. In the current inkjet printers, a fixed actuation pulse is used, which neglects the above mentioned problems. Fig. 4 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 vibrations and cross-talk.
To this end, a Model Predictive Control is proposed to design an input pulse such that the residual vibrations are suppressed. For this purpose, we develop a model of the printhead. A lot of efforts have been made to model the ink channel (Wijshoff (2008) and Wassink (2007)). Here, we will consider a model relating the piezo input voltage (i.e., the input) to the velocity of the so-called meniscus (i.e., the output). The meniscus is the ink and air interface in the nozzle. We consider this model since the velocity of the meniscus is a good measure of the pressure in the ink channel. Consequently, reducing the residual oscillations of the meniscus velocity is equivalent to reducing the residual pressure oscillations in the ink channel. The cross-talk effect is not considered in the pulse design.

4. MODEL PREDICTIVE CONTROL

Model (Based) Predictive Control (MPC) is a method of advanced control originated in late seventies and early eighties in the process industries (oil refineries, chemical plants,...) (J. Richalet and Papon (1976), Peterka (1984) and J. Richalet and Papon (1978)). The MPC is not a single strategy, but a vast class of control methods with the model of the process explicitly expressed trying to obtain control signal by minimizing objective function subject to

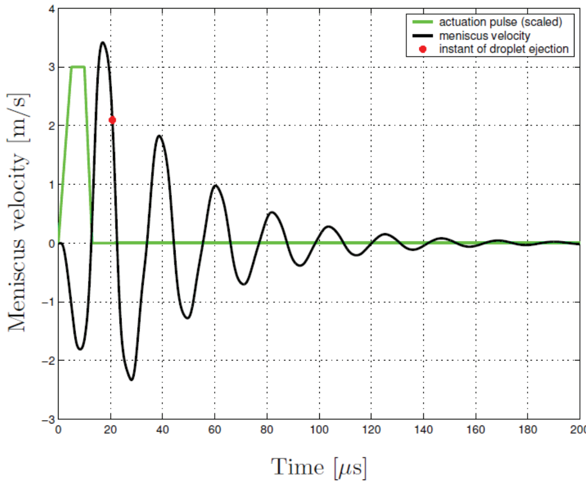

Fig. 3. System response for the standard pulse

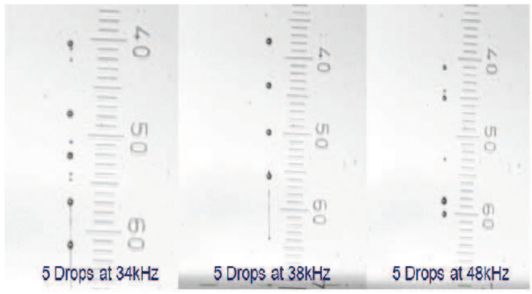

Fig. 4. Jetting 5 drops at different DoD frequencies.

(in general) some constraints.
The MPC strategy comprises two basic steps. First,the future outputs are predicted in an open-loop manner using the model provided information about past inputs, outputs and future signals, which are about to be calculated. The future control signals are calculated by optimizing the objective function, i.e. chosen criterion, which is usually in the form of quadratic function. The criterion constituents can be errors between the predicted signal and the reference trajectory $y_d(k)$, control effort $u(k)$, and rate of change in control signals. Second, the first component of the control sequence $u(k)$ is applied to the system, while the rest of the sequence is disposed. At the next time instant, new output $y(k+1)$ is measured and the control sequence is recalculated, first component $u(k+1)$ is applied to the system and the rest is disposed. This principle is repeated continuously (receding horizon). The reference trajectory $y_d(k)$, the meniscus speed in our case, is known in advance as a jetting pattern. The major advantage of MPC is the ability of computing the outputs $y(k)$ and corresponding input signals $u(k)$ in advance, that helps to avoid sudden changes in control signal and avoid the undesired effect of delay in system response. Stability of the constrained receding horizon has been discussed in Rawlings and Muske (1993) and Zheng and Morari (1994). In this section, an MPC is designed to optimize the performance of the inkjet channel taking into account the jetting pattern.

4.1 Printhead model

Several analytic and numerical models are available for the inkjet channel dynamics in the literature. The 'narrow-gap model' is utilized for MPC synthesis purpose. It describes the dynamics of one ink channel from the piezo input voltage $u(t) \in \mathcal{R}$ to the meniscus velocity $y(t) \in \mathcal{R}$. The detailed derivation of the model for the considered DoD inkjet printhead using the narrow channel theory is given in Wijshoff (2008). The frequency response of this model is shown in Fig. 5. A low order stable transfer function $G(z)$ is identified to fit to the frequency response obtained from the narrow-gap model, see Fig. 5. The choice of the desired meniscus speed $y_d(t)$ is a crucial issue. Fig. 6 shows the reference meniscus speed for one drop, it is chosen such that it contains two main parts, the first part determines the drop properties, i.e. drop speed and volume, the second part is responsible for refilling of the channel. If the actuation pulse $u(t)$ is designed such that the meniscus velocity $y(t)$ follows the desired trajectory $y_d(t)$, then the channel will come to rest very quickly after jetting the drop. This will reduce the interaction between the jetted drops at higher jetting frequencies.

4.2 MPC problem formulation

Consider the printhead system $G(z)$, which is expressed as

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned} \tag{1}$$

where $x(k) \in \mathcal{R}^n$ represents the model state vector with order $n = 16$, and A, B, C, D are the state space realization matrices of $G(z)$ with appropriate dimensions.
The problem is to find a control sequence, $u(k) \in \mathcal{R}$, over the prediction horizon of length N by minimizing the objective function

$$\mathcal{J} = \sum_{0}^{N-1} \left(e(k)^\top Q e(k) + u(k)^\top R u(k) \right) \tag{2}$$

subject to

$$\begin{aligned} u_{min} \leq u(k) \leq u_{max} \\ e_{min} \leq e(k) \leq e_{max} \end{aligned} \tag{3}$$

where $e(k) = y(k) - y_d(k)$ is the tracking error, u_{min}, u_{max}, e_{min}, e_{max} are the maximum and minimum values of the control signal and error of the output signal from reference, respectively. $Q \succ 0$ and $R \succ 0$ are weighting matrices of output error and control effort, respectively. The printhead under investigation has very limited control capabilities. There is no sensor for real-time measurement of the channel pressure or the meniscus velocity. Moreover, the sampling time required for control computation has to be very short, i.e. $T_s = 0.1$ μsec, due to high drop jetting frequency. Thus the MPC is used to design the actuation pulse offline based on the known jetting pattern. The values of the input constraint limits are chosen based on the driving circuit limits with $u_{min} = -30V$ and $u_{max} = 50V$.

5. SIMULATION AND EXPERIMENTAL RESULTS

In this section, the proposed MPC is applied to the printhead. Both simulation and experimental results are used to investigate the performance of the proposed approach and to compare with the performance of the currently used standard input pulse.

5.1 Simulation results

In this section, we compare the simulation results for the MPC and the currently used standard pulse. The MPC is used to look ahead over the jetting of two droplets while the control horizon is chosen to jet one droplet. Fig. 7 shows the response of jetting one drop. It is clear that the residual oscillations have been highly damped using the MPC input. Fig. 8 shows the simulation results of jetting 10 drops at 60 kHz. For the standard pulse, the meniscus velocity does not quickly come to rest after jetting a droplet, therefore, the initial meniscus position is different before jetting the subsequent that causes a difference in the velocity-peaks for the subsequent drops which is indeed observed in Fig. 8. Note that the velocity peak is a major feature and that a changed velocity-peak will result in drops having different velocities. on the other hand, the MPC input is able to highly damp the residual oscillations that ensures same initial meniscus position for all the subsequent drops. The difference in the velocity-peaks of the proposed MPC input is negligible, that will result in a consistent drop properties for all drops.

5.2 Experimental results

A schematic overview of the experimental set-up is depicted in Fig. 9. With this set-up, inkjet printheads can be investigated in various ways. The only actuator is the piezo-unit of the inkjet printhead. Two sensors are available in this set-up:

- 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.
- A Charge-Couple Device (CCD) camera,equipped with a microscope, which is used to monitor the properties of the resulting droplet

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.
The simulation results show that a considerable improvement can be achieved by implementing the MPC compared with the performance of the standard pulse. Thus, the MPC input is applied to a real printhead and the results are compared with a standard pulse. The MPC input is used to jet 10 drops at different jetting frequencies. The

time history of the drop traveling form the nozzle plate to the paper are collected to analyze the performance of the printhead. Fig. 10 shows the time history of the 10 drops jetted at at 42 kHz for both the MPC input and standard pulses. 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 MPC pulse shows that the drop speed of the 10 drops are almost the same. A number of experiments were carried out for different jetting frequencies ranging from 20 kHz to 70 kHz. The drop speed of each of the 10 drops are depicted in Fig. 11 and 12. The performance is evaluated based on maximum drop speed variation at each DoD frequency and the maximum drop speed variation over the whole range of the DoD frequencies, e.g. 20-70 kHz. The maximum drop speed variation at each jetting frequency is calculated as

$$\begin{aligned} \Delta v(f) &= v_{max}(f) - v_{min}(f) \\ \Delta v_{max} &= \max_{f} \Delta v(f) \end{aligned} \tag{4}$$

The maximum drop speed variation is less than 1.5 m/sec for the MPC input while it is 2.5 m/sec for the standard pulse. The maximum drop speed variation at each jetting frequency is calculated as the difference between the fastest drop and the slowest drop over the whole range of jetting frequencies. We found that using the MPC input the drop speed variation over all the DoD frequencies is reduced to 2 m/sec rather than 10 m/sec in case of the standard pulse. The overall improvement in the drop speed consistency achieved using the MPC has a far reaching consequences for the print quality.

6. CONCLUSION

In this paper, an MPC has been proposed to damp the residual vibrations in an inkjet channel without influencing the droplet formation taking into account the jetting pattern. 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. It has been demonstrated that the MPC is a suitable control strategy to overcome the residual vibrations and hence increases the performance of inkjet printhead considerably, beyond current limits. The experimental results have shown a considerable improvement in the drop-consistency the inkjet printhead using the proposed approach.

The extension of the control framework to MIMO control to further reduce the effect of cross-talk while actuating multiple channels simultaneously is subject to ongoing research.

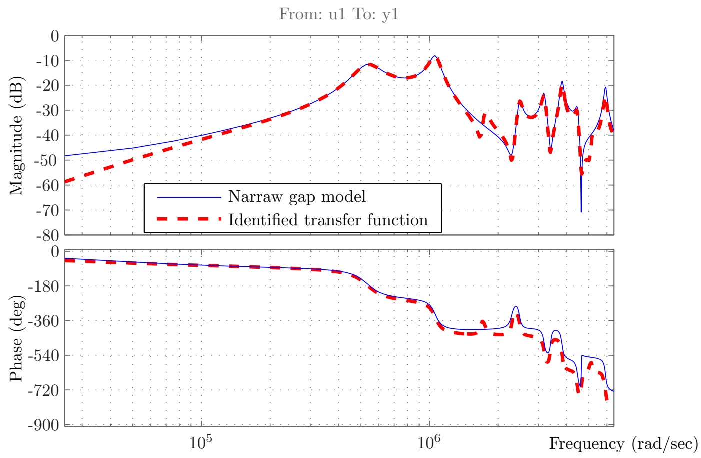

Fig. 5. Frequency response of the narrow gap model (solid line) and the fitted transfer function(dash line).

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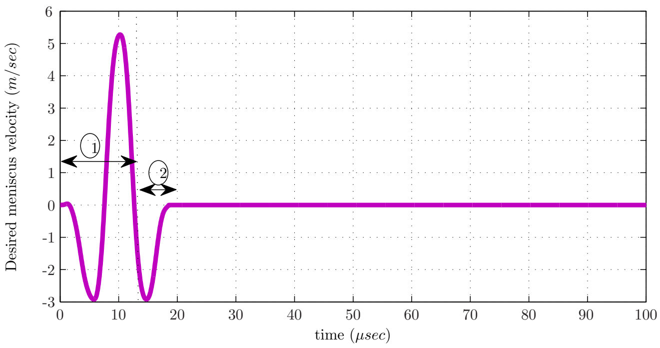

Fig. 6. Reference meniscus velocity.

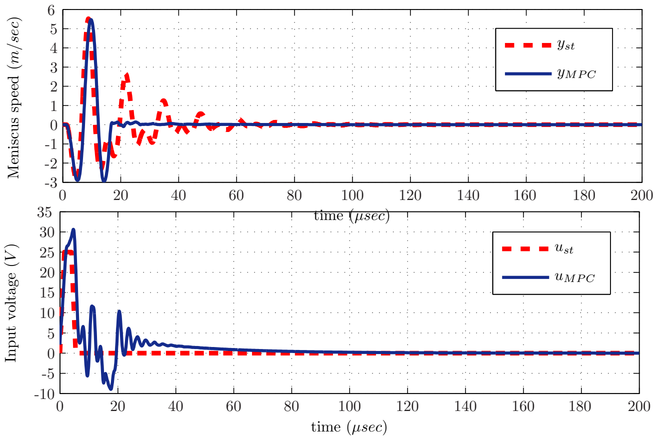

Fig. 7. System response for jetting one drop.

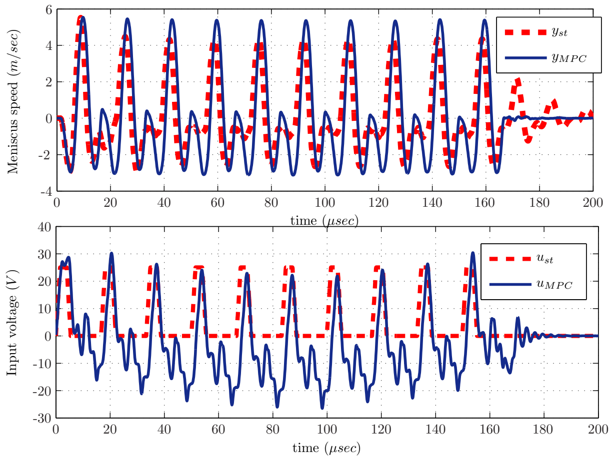

Fig. 8. System response for jetting 10 drops at 60 kHz.

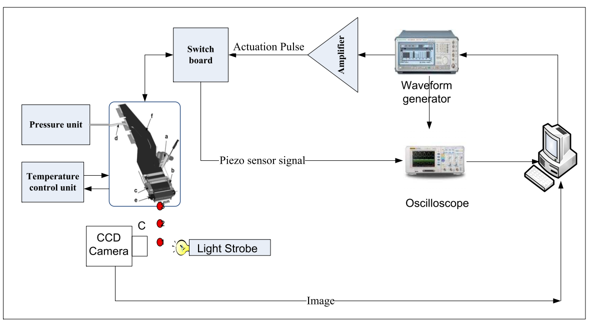

Fig. 9. Experimental set-up.

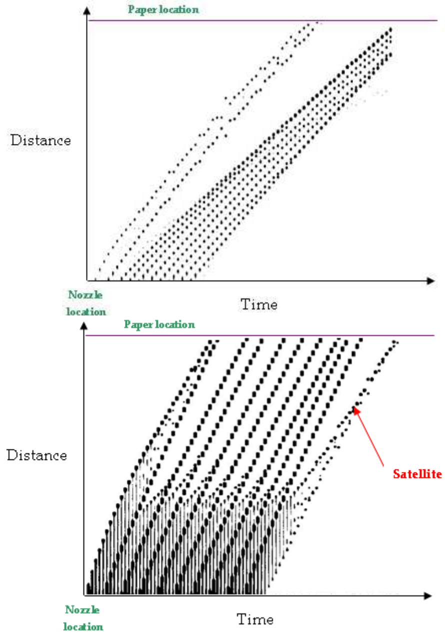

Fig. 10. Drop time history for jetting 10 drops at 42 kHz with standard pulse (Upper plot) and proposed pulse(bottom plot).

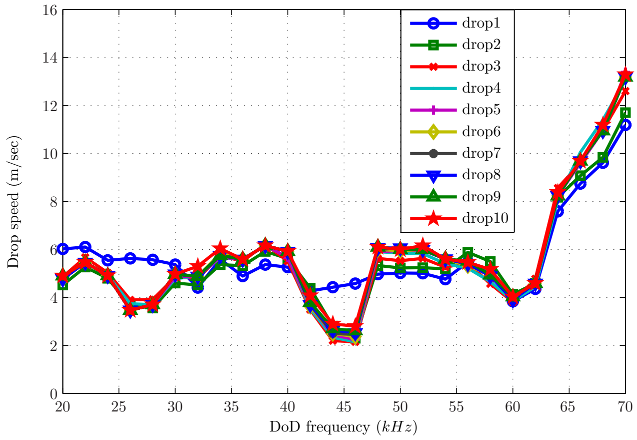

Fig. 11. Standard pulse: Jetting 10 drops at different DoD frequencies (20-70 kHz).

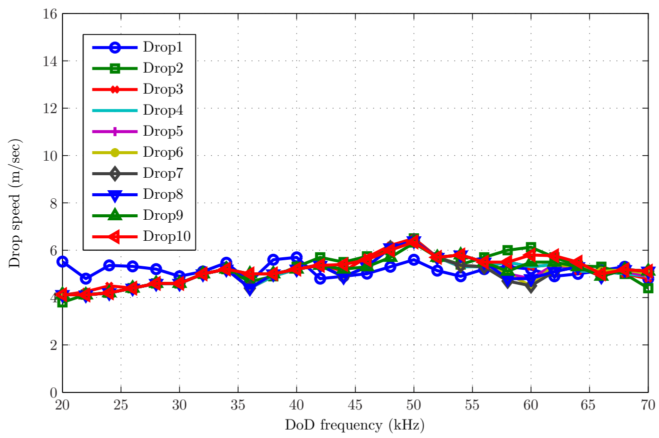

Fig. 12. Proposed pulse: Jetting 10 drops at different DoD frequencies (20-70 kHz).