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Inverse-Based Feedforward Control for an Inkjet Printhead

M. Ezzeldin, P.P.J. van den Bosch and S. Weiland

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 droplets which are small and 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. This makes the printing quality an important issue. In this paper, a model-based and data-based inverse feedforward control method is proposed to improve the printing quality of the piezoelectric inkjet printer. The proposed inverse input is applied to the inkjet printhead and the system performance is investigated.**

I. INTRODUCTION

Inkjet printing uses ink droplets to form patterns on a substrate. Inkjet printing has been widely used for depositing ink onto paper in daily office and home apparatus. In inkjet printing technology, the volume of a droplet from the inkjet dispenser can be controlled to an accuracy of picoliters. In addition, the droplet can be placed onto a substrate to an accuracy of micrometers. Because of these specifications, inkjet technology has recently emerged as one of the most powerful tools for patterning electronic devices such as display applications. Inkjet patterning is an additive process, where multiple patterns of layers can be added to without any removal of previously deposited materials. Therefore, material waste can be significantly reduced by using inkjet technology. Consequently, activities in the development of inkjet printing for depositing electronic materials have increased in the last few years [1] - [4].

Inkjet technology can be categorized into two types: bubble jet (thermal inkjet) and piezoelectric inkjet. A thermal inkjet printer uses a heating element to heat liquid ink so as to form vapor bubbles, which forces the ink droplets to leave the nozzle of the printer. Thermal inkjet has been widely used for low-end color printers. On the other hand, 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. Essentially this is the same mechanism as the thermal inkjet but it generates the pressure pulse using a different physical principle. A piezoelectric inkjet printing allows a wider variety of ink 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 jetting frequencies. Meeting such performance requirements is severely hampered by several operational restriction that are associated with the design and operation of printheads. Major issues that are generally encountered are residual vibrations and cross-talk (see Section III). In this paper, model-based and data-based feedforward inverse controllers are proposed to design the input actuation pulse for the piezoelectric inkjet printer to improve the printing quality by minimizing the effects of these operational restrictions.

Model-based feedforward inversion of system dynamics, can be used to find inputs that achieve high-precision output tracking; this input is referred to as the *inverse input*. The inversion technique has been applied to a number of output tracking applications; for example, in the precision control of flexible manipulators, aircraft control, and high-precision positioning of piezo probes for nanoscale imaging using scanning-probe microscopy. Common difficulties in realizing a model-based inversion strategy, however, are that it may produce unbounded or oscillatory outputs. This will occur when the system is non-minimum phase. Moreover, the inverse input will be erroneous if the modeling uncertainty is large. These difficulties have been addressed in the development of optimal-inversion techniques in [5]. In particular, the optimal-inversion technique proves useful to account for modeling errors by only inverting the system model in frequency regions where the modeling uncertainty is sufficiently small [6]. However, a challenge in implementing the optimal-inversion approach is that the resulting inverse input tends to be noncausal [6]. This means that knowledge of the entire future desired output trajectory is needed to compute the inverse input at the current time instant. The noncausality of the inverse input restricts the stable-inversion technique to trajectory-planning applications only. This restriction is alleviated through the development of the preview-based approach to the stable-inversion technique [7], which obtains the inverse input by using a finitely previewed trajectory rather than the entire (i.e.,infinite-previewed) future desired trajectory.

In this paper, a data-based feedforward inverse controller technique is proposed. The proposed approach is based on calculating the inverse function of the measured frequency response of the system. Based on the inverse frequency response of the system, the inverse input is calculated in

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M. Ezzeldin, P.P.J. van den Bosch and S. Weiland are with the Department of Electrical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands. m.ezz@tue.nl, p.p.j.v.d.bosch@tue.nl, s.weiland@tue.nl

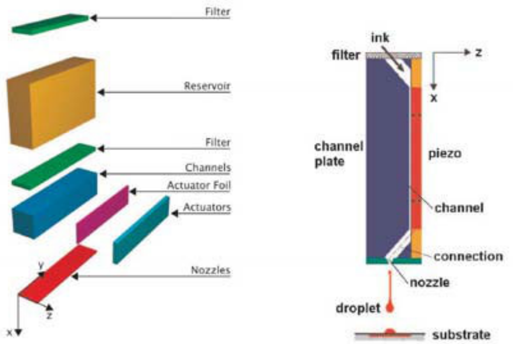

Fig. 1. Exploded view of a piezoelectric inkjet printhead (left) and schematic representation of a single channel (right).

the frequency-domain for a given desired output. Then the inverse input is transformed to the time-domain. The main advantages of the proposed inverse controller is that there is no error due to model uncertainty since our approach is based on measured data. Moreover, the inverse input will be always bounded since it is calculated first in the frequency domain which is always bounded that results into a bounded time domain inverse input.

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 inverse feedforward control design. Simulation and experimental results are given in Section V. Finally, concluding remarks are collected in Section VI.

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, a 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. [10] and [11]. First, a negative pressure wave is generated in the channel by enlarging the volume in the channel. This pressure wave splits 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 reflected 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:

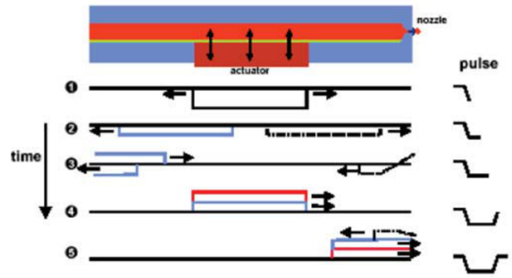

Fig. 2. Drop jetting mechanism

- *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.

III. Problem Statement

Meeting the above 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. Traveling pressure waves remain present after a drop has been jetted. 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 the case 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

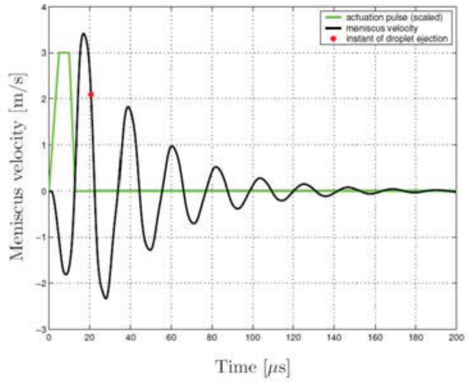

Fig. 3. System response for the standard pulse

is referred to as *direct voltage cross-talk*. The second one is the result of the resulting 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. 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.

In this paper, a model-based and data-based inverse feed-forward controller 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 [8], [9]. 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.

IV. Feedforward Inverse Control

In this section, we first present a model-based inverse control principle proposed by [7]. Then, a data-based feed-forward inverse control approach is proposed.

A. Model-based inverse control

The inversion problem is presented as the minimization of a quadratic-cost function and the optimal inverse is obtained as a filter as developed in [7].

Consider a linear-time invariant (LTI) system:

$$\dot{x}(t) = Ax(t) + Bu(t), \tag{1}$$

$$y(t) = Cx(t) + Du(t), \tag{2}$$

where $x(t) \in \Re^n$ is the system state, and the number of inputs is the same as the number of outputs, $u(t) \in \Re$ and $y(t) \in \Re$, i.e. the system is square. The transfer function is given by

$$G(s) = C(sI - A)^{-1}B + D \tag{3}$$

Assume that system (2) is invertible as a rational operator, i.e there exists a transfer matrix $G^{-1}(s)$ such that $G^{-1}(s)G(s) = I$, moreover, system (2) and its inverse are analytic on the imaginary axis.
For a sufficiently smooth desired output $y_d(t) \in L_2$ the optimal inversion problem is to minimize the following cost function [7]:

$$J(x_o, u) = \int_0^\infty \{u(t)^\top Ru(t) + [y(t) - y_d(t)]^\top \times Q[y(t) - y_d(t)]\}dt \tag{4}$$

Here, R and Q are weighting functions.
Define

$$G_{opt}(s) := [R(s) + G^*(s)Q(s)G(s)]^{-1}G^*(s)Q(s) \tag{5}$$

The optimal inverse can be found using a filter $G_{opt}(s)$ as follows

$$u_{opt}(s) = G_{opt}(s)y_d(s) \tag{6}$$

Assume that $G_{opt}(s)$ is proper (by proper choice of R, Q). The inverse filter $G_{opt}(s)$ can be decomposed into a stable and anti-stable part

$$G_{opt}(s) = G^{st}_{opt}(s) + G^{as}_{opt}(s) \tag{7}$$

where

$$\begin{aligned} G^{st}_{opt}(s) &= C_{st}(sI - A_{st})^{-1}B_{st} + D_{st} \\ G^{as}_{opt}(s) &= C_{as}(sI - A_{as})^{-1}B_{as} + D_{as} \end{aligned} \tag{8}$$

where $A_{st}, B_{st}, C_{st}, D_{st}$ and $A_{as}, B_{as}, C_{as}, D_{as}$ are the state space realizations of $G^{st}_{opt}(s)$ and $G^{as}_{opt}(s)$ respectively. The bounded solution to the optimal inversion problem is then obtained by flowing the stable portion forward in time and flowing the anti-stable part backward in time [7] as indicated in the following lemma.

Lemma 1: Let the desired output $y_d(t)$ be bounded uniformly in time $t \in (-\infty, \infty)$. The bounded optimal solution to the optimal inverse input $u_{opt}(t)$ for all time $t \in (-\infty, \infty)$ is given by

$$\begin{aligned} u_{opt}(t) &= u^{st}_{opt}(t) + u^{as}_{opt}(t) \\ u^{st}_{opt}(t) &= C_{st}\int_{-\infty}^{t} e^{A_{st}(t-\lambda)}B_{st}y_d(\lambda)d\lambda + D_{st}y_d(t) \\ u^{as}_{opt}(t) &= -C_{as}\int_{t}^{\infty} e^{A_{as}(t-\lambda)}B_{as}y_d(\lambda)d\lambda + D_{as}y_d(t) \end{aligned} \tag{9}$$

Remark 1: The computation of the optimal inverse input (9) at any time t, requires the knowledge of all future values of the desired output $y_d(t)$. In particular, the computation of $u^{as}_{opt}(t)$ in (9) requires knowledge of all future values of the desired output $y_d(t)$ for time interval $[t,\infty)$. However, $u^{as}_{opt}(t)$ can be approximated by truncating the integral in (9), by only using information of the desired output during finite time interval $[t,t+T_p]$as follows

$$\hat{u}^{as}_{opt}(t) = -C_{as}\int_{t}^{t+T_p} e^{A_{as}(t-\lambda)}B_{as}y_d(\lambda)d\lambda + D_{as}y_d(t) \quad (10)$$

hence, the finite-preview based optimal inverse input is given by

$$\hat{u}_{opt}(t) = u^{st}_{opt}(t) + \hat{u}^{as}_{opt}(t) \quad (11)$$

Note that the finite-preview based implementation leads to tracking errors, it is clear that the tracking error can be made arbitrarily small by choosing a sufficiently large preview time T_p. In addition, this approach is highly sensitive to model uncertainties.

B. Data-based inverse control

For data-based inversion, the key point is to utilize the inverse of the system dynamics from the frequency-domain implementation scheme. A schematic diagram for the proposed approach is shown in Fig. 4.
If $(U(jw),Y(jw))$ is the frequency response data, then a data-based estimate of the system transfer function is

$$G(jw) = \frac{Y(jw)}{U(jw)} \qquad w \in \Re \quad (12)$$

where $Y(jw)$ and $U(jw)$ are the frequency-domain representation of the system output and input respectively. The inverse frequency response of the system is obtain as follows

$$G_{inv}(jw) = \frac{U(jw)}{Y(jw)} \qquad w \in \Re \quad (13)$$

Let the desired output $y_d(t)$ be periodic and have finite energy, i.e. $y_d(t) \in L_2$. Then the inverse input can be calculated in the frequency-domain as

$$U_{inv}(jw) = G_{inv}(jw)Y_d(jw) \quad (14)$$

Finally the feedforward inverse input is transformed to the time-domain

$$u_{inv}(t) = \mathscr{F}^{-1}(U_{inv}(jw)) \quad (15)$$

with $\mathscr{F}^{-1}$ is inverse Fourier operator. *Remark 2:* This approach is based on measured data which make it insensitive to model uncertainties. However, the measured data should be sufficiently rich to capture the system dynamics. The causality-related limitations in the model-based inverse control approaches are removed with the development of the data-based inversion control approach. Particularly, the data-based inversion approach utilizes the inverse of the system dynamics from a frequency-domain implementation scheme. Due to the properties of the Fourier transform, the inverse input (15) will be always bounded even in case of the inversion of non-minimum phase system.

V. Simulation and Experimental results

In this section, the proposed feedforward inverse control is applied to the printhead. Both simulation and experimental results have been performed to investigate the performance of the proposed inverse control inputs and to compare with the performance of the currently used standard input pulse.

A. Simulation results

In this section, the model-based and data-based inverse control are applied to minimize the effect of the residual vibration in the inkjet channel. Several analytic and numerical models are available for the inkjet channel dynamics in the literature. The narrow-gap model is utilized for inverse control synthesis purpose. It describes the SISO dynamic system from the piezo input voltage u to the meniscus velocity y. The detailed derivation of the model for the considered DoD inkjet printhead using the narrow channel theory is given in [8]. Note that the system is non-minimum phase which can be observed in Fig. 3. The frequency response of this model is shown in Fig. 5. This empirical frequency function can not be used for the design of the model-based inverse control (9). Therefore, a low order transfer function $G(s)$ is identified to fit the frequency response obtained from the narrow-gap model, see Fig. 5. On the other hand, the empirical frequency function of the narrow gap model is used directly to design the inverse control input (15). The choice of the reference meniscus speed is a crucial issue. As shown in Fig. 6, 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 after that it will settle at zero to ensure zero initial condition of the subsequent drop. With the perfect tracking of the feedforward inverse control, the residual oscillations will be damped out. We compare both the model-based and data-based inverse input with the standard pulse in Fig. 7. Figures 8-9 show the simulation results of jetting 10 drops at 40 kHz. For the standard pulse, the meniscus velocity does not quickly come to rest after jetting a droplet. Therefore, the initial meniscus position is non-zero before jetting the next pulse this causes a difference in the velocity-peaks for the subsequent drops, which is indeed observed in figures 8-9. Recall that the velocity-peak is a major feature and that a changed velocity-peak will result in drops having different velocities. The feedforward inverse inputs are able to highly damp the residual oscillations and ensure the same initial meniscus position for all subsequent drops. The difference in the velocity-peaks of the proposed inverse inputs is negligible. Consequently, this controlled scheme will result in consistent drop properties for all drops. As depicted in Fig. 10, the meniscus velocity tracking error of the data-based inverse control is less than the model-base inverse control.

B. Experimental set-up

A schematic overview of the experimental set-up is depicted in Fig. 11. With this set-up, inkjet printheads can be

Bode Diagram

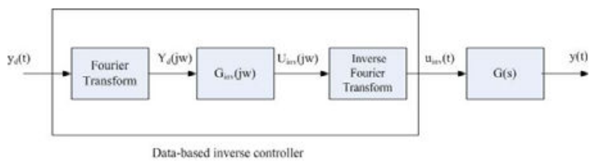

Fig. 4. Data-based inverse feedforward control approach.

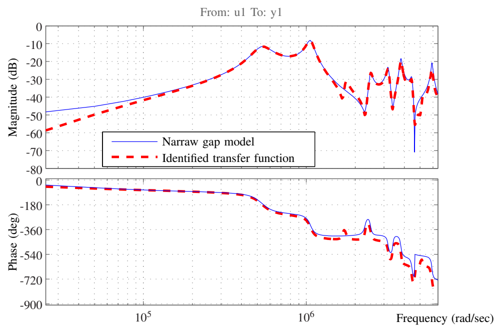

Fig. 5. Frequency response of the narrow gap model (solid line) and the fitted transfer function(dash line).

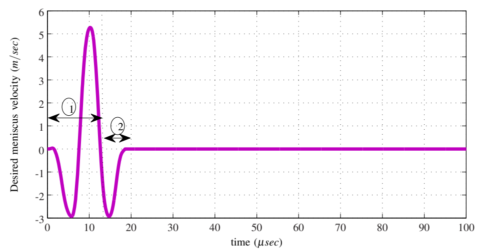

Fig. 6. Reference meniscus velocity.

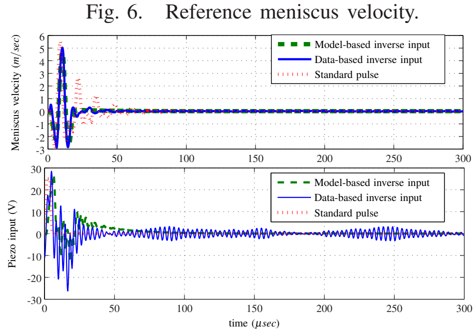

Fig. 7. System response for jetting one drop.

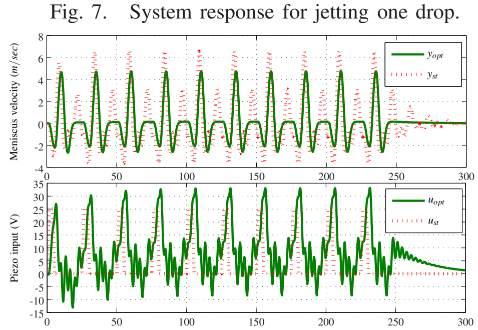

Fig. 8. System response for jetting 10 drops at 40 kHz.

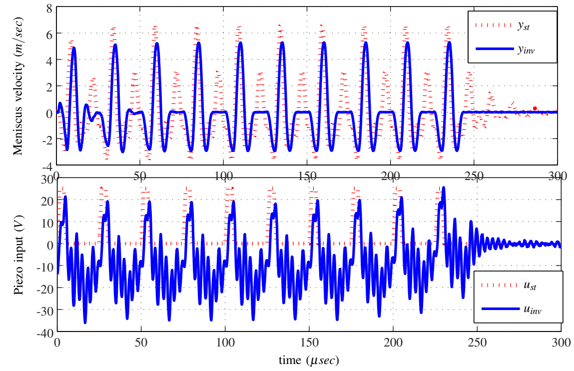

Fig. 9. System response for jetting 10 drops at 40 kHz.

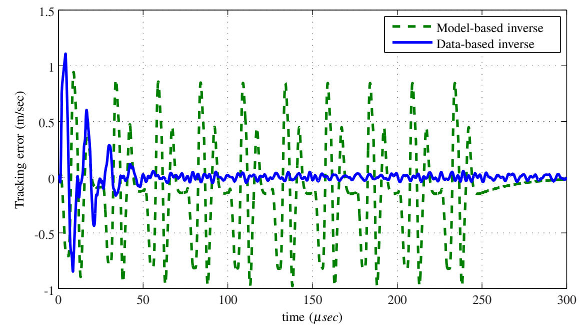

Fig. 10. Meniscus velocity tracking error.

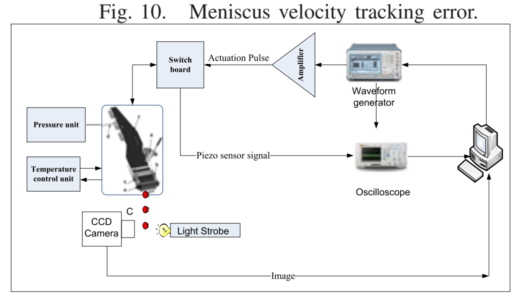

Fig. 11. Experimental set-up.

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

A stroboscope provides a short light flash at a well 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.

C. Experimental results

The simulation results show that a considerable improvement can be achieved by implementing the feedforward inverse control. It has been shown that the data-based inverse control results in a smaller tracking error compared with model-based approach. Thus, the proposed data-based inverse feedforward control is applied to a real printhead and the results are compared with a standard pulse. The data-based inverse control 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. A number of experiments are carried out for different jetting frequencies ranging from 20 kHz to 70 kHz. The drop speed of each of the 10 drops using the standard pulse and the proposed inverse control input are depicted in Fig.12 and 13 respectively. 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

$$\begin{aligned} \Delta v(f) &= v_{max}(f) - v_{min}(f) \\ \Delta v_{max} &= \max_f \Delta v(f) \end{aligned} \tag{16}$$

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 proposed inverse control 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 feedforward inverse control has a far reaching consequences for the print quality.

VI. CONCLUSIONS

A feedforward inverse control has been proposed to improve the performance of the inkjet printhead. A model-based and data-based inverse control schemes are proposed. 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 increases the performance of inkjet printhead considerably, beyond current limits. The experimental results have shown the efficiency of 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.

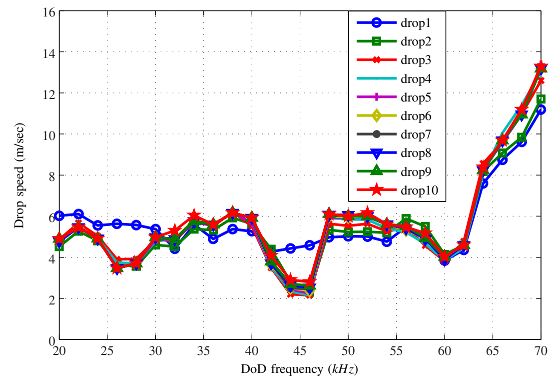

Fig. 12. Standard pulse: Jetting 10 drops at different DoD frequencies (20-70 kHz).

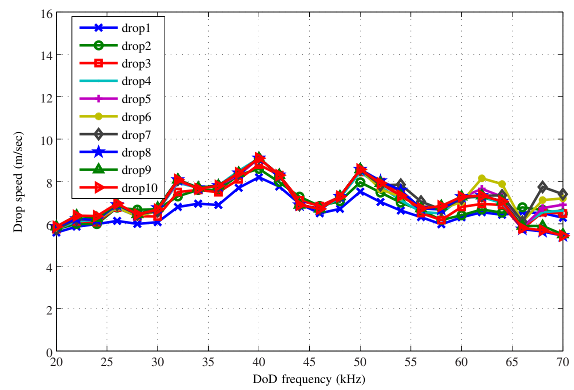

Fig. 13. Proposed pulse: Jetting 10 drops at different DoD frequencies (20-70 kHz).

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