Enabling Higher Jetting Frequencies for Inkjet Printheads Using Iterative Learning Control

M. B. Groot Wassink and O. H. Bosgra, Delft University of Technology, Delft, The Netherlands
M. Slot, Océ-Technologies B.V., Venlo, The Netherlands

Abstract
Inkjet printheads operate thanks to resonating fluid- mechanics. At the same time, however, this limits the attainable jetting frequency since the residual vibrations must be damped first prior to jetting a next droplet. This paper presents an approach based on lifted ILC with which input wave forms are designed that leave the droplet formation undisturbed while bringing the channel to a rest quickly after droplet ejection. This paper shows the modeling required for ILC, the design of the ILC controller in the lifted setting with separate observation and actuation windows, and the experimental implementation.

Introduction
Inkjet technology is an important key-technology from an industrial point of view. Its ability to deposit various types of material on a substrate in certain patterns makes it a very versatile technology. Not surprisingly, applications of this technology cover a wide range from the traditional document printing to the manufacturing of electronics such as Flat Panel Displays (e.g. Refs. [1] and [7]), the production of organic electronics (e.g. Ref. [2]), and the use for rapid prototyping (e.g. Ref. [10]). Each specific field of application imposes its own performance requirements on the inkjet printhead. First, specifications in terms of timing, positioning, and volume have to be met. Often, these criteria are quite tight. Typically, one can think of an accuracy to be met in terms of fractions of microseconds, micrometers and picoliters. Second, requirements play a role concerning reproducibility in face of aging, material and ink variations, and the like. In the future, these performance criteria become even tighter. The requirements for future applications motivate ongoing research into inkjet technology.

A typical design of a printhead comprises several piezo- actuated channels in parallel. Given a certain design of these channels, the piezo-actuators are provided with pulses (wave forms), whose shape has been the result of a design based on physical insight, such that the requested drop on demand (DOD) results. This approach in combination with printhead designs has become mature and its possibilities have been exhausted, especially in face of some operational issues that are generally encountered:

- The strive for higher jetting frequencies. After droplet ejection, the ink in a channel is usually not at rest immediately. Typically, it takes around 200 μs for the pressure waves to be damped such that a next droplet can be jetted: this to guarantee the same droplet properties each time a channel is actuated. Therefore, the maximum attainable jet frequency is limited by these resonating fluid-mechanics.
- The elimination of cross-talk. If one channel is actuated, neighboring channels are influenced by both structural and acoustical cross-talk. This results in different droplet properties if neighboring channels are actuated simultaneously.
- The changing dynamics. Due to for example aging, production differences, and ink variations the same actuation signal does not always result in the same droplet properties.

The switch to a control-based approach for an inkjet printhead can break these boundaries. Since at this point feedback control is considered computationally infeasible due to the small time scales involved, our attention is directed to feedforward control. More specifically, given the highly repetitive character of the jetting process, Iterative Learning Control (ILC) is a logical choice as control strategy.[4-6] Though ILC has proven its value for high-precision motion systems (e.g., Refs. [3] and [15]), it seems its use in the field of inkjet technology is novel. We will show the great benefits of ILC for this area, especially with regard to the realization of higher jetting frequencies.

The paper is organized as follows. First, a system description is provided and the experimental modeling is discussed. Second, the control structure, the specification of the control goal, and the design of the ILC controller in the lifted setting are treated. Next, some experimental results are presented. Finally, the conclusions are drawn and an outlook on future work is given.

System Description
A schematic view of a channel of an inkjet printhead is depicted in Fig. 1. It consists of a channel of several millimeters, a nozzle, and a piezo-unit. Typically, around 75 nozzles per inch are integrated in an array that forms a printhead. To fire a droplet, a trapezoidal pulse is provided to the piezo actuator. Then, ideally, the following occurs. To start with, a negative pressure wave is generated in the channel by enlarging the volume in the channel (step 1). This pressure wave splits up and propagates in both directions (step 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 (step 3). Note that the pressure wave reflecting at the nozzle is not large enough to result in a droplet yet. Next, by decreasing the channel's volume to its original value a positive pressure wave is superposed on the reflected waves exactly when they are located in the middle of the channel (step 4). Consequently, the wave traveling towards the reservoir is cancelled whereas the wave traveling towards the nozzle is amplified such that it is large enough to result in a droplet (step 5). Typically, a printhead is operated at 10 kHz. It takes about 20 μs to fire a droplet and around 200 μs for the pressure waves to

be completely damped. Note that after 100 μs the pressure waves are sufficiently damped such that they do not affect the next droplet negatively.

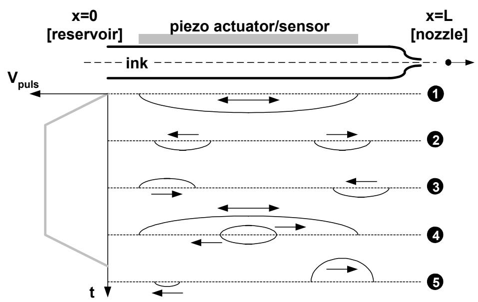

Figure 1. A schematic view of an inkjet channel and its working principle

According to Ref. [9], the piezo-unit is concurrently used as actuator and sensor. Physically, it senses the force that results from the pressure distribution in the channel acting on the piezo's surface that borders the channel. This force creates a charge on the piezo unit. Since only changes in charge are measured, in fact the time derivative of the instantaneous present force is sensed. Furthermore, since the resulting voltage drop of this current over a resistance is measured, we have that a voltage is the resulting sensor signal. For the trapezoidal pulse used for actuation, a typical sensor signal is depicted in Fig. 3. The following remarks are in order. First, the sensor is located in the channel whereas the droplet formation takes place in the nozzle. Second, due to the integrating character of the sensor the resulting signal is an average of the pressure that is present in a channel. Finally, since all the piezo's are connected to the same substrate, the actuation as well as sensing is influenced by cross-talk. Nevertheless, the current sensor signal can be regarded representative for the jetting process. This assumption forms a basis for the work presented here.

When control is applied to an inkjet printhead, it is tacitly assumed that the operation of a channel is linear. However, the ejection of a small volume of ink introduces non-linear behavior. It will be shown that despite this effect, the printhead system still can be regarded as dominantly linear, see the next section.

Experimental Modeling

For the modeling of the printhead system, we can utilize both theoretical and experimental modeling. Theoretical modeling has been given quite some attention over the years, see e.g. Ref. [8]. Still, modeling a printhead system theoretically is far from trivial and often involves a combination of (non-linear) piezo behavior, acoustics, and fluid-mechanics including droplet formation. Usually, the resulting models are a trade-off between accuracy and computational load. For control, it is desirable to have both reasonable accuracy and small computational load. Recently, we have developed a theoretical model that fulfills these criteria.[17] Though this model already has been used successfully as starting point for the implementation of ILC for an inkjet printhead, we resort in this paper to experimental modeling for reasons of generality and simplicity.

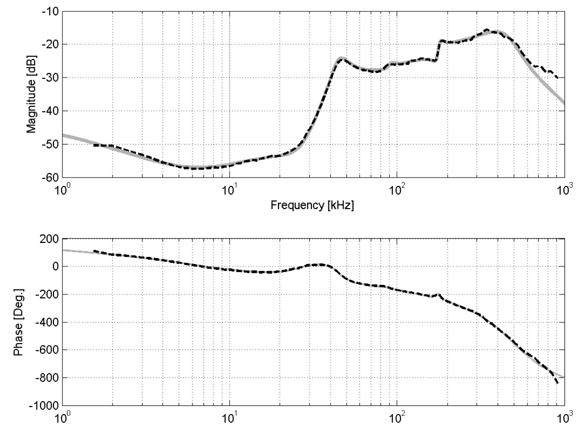

Figure 2. FRF from the piezo actuator to the piezo sensor; (black dotted) and model (gray)

To that purpose, a sine-sweep was used to identify the accompanying frequency response function (FRF) from the piezo actuator to the piezo sensor, see Fig. 2. The amplitude of the sinusoids was chosen such that the inkjet channel was not jetting. The measured transfer function includes among other things the piezo amplifier and a low-pass filter with a cut-off frequency of 500 kHz. The latter is used to eliminate the high-frequent piezo behavior. The amplifier and low-pass filter cause a significant phase drop at high frequencies. The resonance frequencies visible in Fig. 2 can be interpreted as the occurring standing wave in an inkjet channel and its higher order modes. Note that these resonance modes are highly damped.

A weighted OE least-squares approximation was used to obtain a linear model.[11] The resulting 16th order model is also depicted in Fig. 2. To assess the quality of the obtained model and the linearity of the jetting process, it has been validated using a measured sensor signal, see Fig. 3. This sensor signal is the result of a standard trapezoidal pulse at a jetting frequency of 10 kHz. Based on Fig. 3, we conclude that the dynamics are modeled quite accurately. Apparently, the non-linearity originating from the ejection of a droplet is not that influential. Though the firing of a droplet causes an increase of the residual vibration frequencies within an inkjet channel, differences after the droplet ejection (approximately 20 μs) between measured and model response are quite small. From a control perspective, the operation of a printhead thus can be regarded as linear. The remainder of the modeling errors originates mainly from piezo non-linearities. Despite the discussed modeling errors, the obtained experimental model forms a suitable starting point for ILC. The online ILC controller in combination with the actual system can handle these small model inaccuracies quite well.

ILC Design Procedure

In this section, some details regarding the application of ILC to an inkjet printhead are treated. To start with, the control structure is briefly discussed. Next, the control goal is specified. Finally, some practicalities of ILC controller synthesis are discussed.

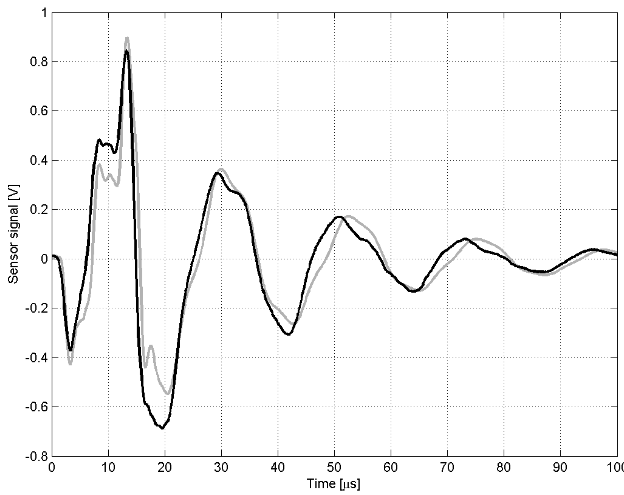

Figure 3. Sensor signal resulting from a standard fixed pulse; measured (black) and model response (gray)

Control Structure

In this paper, use is made of ILC in the lifted setting.[3,4,12] The accompanying control structure is depicted in Fig. 4. The mapping P is the impulse response matrix of the process: it represents the printhead's response to an arbitrary input pulse. This impulse response is computed using the experimental model obtained. The learning matrix, the controller that still has to be designed, is represented by L and may be non-causal and time-varying. z^{-1} is one trial delay operator and can be seen as memory block. Signal u_k is a vector containing the system's inputs or states of the ILC system. Signal y_k is the system output, y_{ref} the reference trajectory, and e_k is the error output. y_{ref} is specified a priori. The update of the system's input is u_k and u_{k+1} is the input for the next trial k+1. During operation, the following occurs. At the k-th trial, signal u_k is provided to the system, resulting in the integrated output y_k. The output y_k is then subtracted from the reference y_{ref} to obtain the error e_k. Based on this error, the learning controller computes the adjustments to the input u_k that, added to the previous input, forms the input for the next trail u_{k+1}. At this point, both y_{ref} and L are to be specified. This is subject of the following two sections.

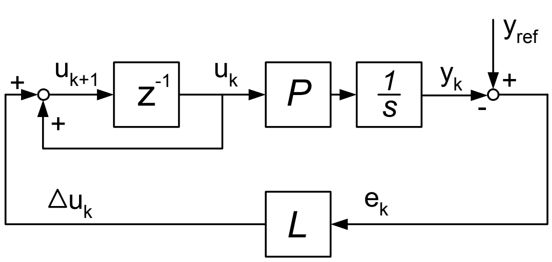

Figure 4. ILC control structure in the trial domain

Control Goal

Basically, the control goal of the ILC controller already has been specified in the introduction, namely achieving higher jetting frequencies while preserving the droplet's properties. By choosing the sensor signal as controlled variable, the question arises how to choose a suitable reference trajectory for the pressure in the channel to accomplish this goal. The following observation forms the key to a proper choice. If the meniscus of the ink in the nozzle follows a certain velocity profile, a droplet of certain properties results, see e.g. Ref. [14]. This meniscus trajectory is directly related to the sensor signal. Therefore, instead of focusing on the droplet properties, it is allowed to direct our attention to the sensor signal as reference trajectory. The transfer function between the sensor signal and the meniscus velocity can be measured using a laser-vibrometer. Based on this transfer function, the desired sensor signal can be computed. For now, the sensor signal resulting from a standard trapezoidal pulse, see Fig. 3, is taken as starting point for the construction of the reference trajectory. To accomplish our control goal, the following procedure is applied. Suppose that this trajectory consists of two parts. During the first part, the trajectory is maintained such that a droplet of certain predefined properties results. Also, deviations from this reference trajectory due to changing dynamics and cross-talk are actively suppressed by the ILC controller. During the second part of the reference trajectory, the fluid-mechanics is brought to a rest as soon as possible after the firing of a droplet. By doing so, the conditions for higher jetting frequencies are created. Again, changing dynamics and cross-talk hardly affects the operation of the printhead due to the active ILC controller.

As discussed during the system description, the sensor signal is in fact a measure of the derivative of the pressure in a channel. If the reference trajectory would be based on that signal, the derivative of the pressure would be controlled. Therefore, the measured output is numerically integrated as can be seen in Fig. 4. As starting point for the construction of the reference trajectory, the integrated version of Fig. 3 is used. The first part up to the firing of a droplet is left unchanged (to 30 µs), whereas during the remainder of the time the pressure is forced to a rest by speeding up the damping. The pressure is not forced to a rest immediately but somehow gradually. This is done to ensure the refill of the nozzle with ink and to avoid too high actuation voltages. Of course, the choice of the reference trajectory should be such that it is controllable. The resulting reference trajectory is depicted in Fig. 5.

In this paper, ILC is elaborated further for a single channel only. However, the expansion of the proposed control strategy for an array of channels is straightforward. More than in the SISO case discussed here, cross-talk effects can be further minimized in the MIMO case using ILC.

ILC Design

For a detailed description for the ILC controller synthesis, one is referred to Refs. [3] and [12]. However, the following remark concerning the application of ILC to the inkjet printhead is in order. As discussed the reference trajectory enforces the active damping of the fluid-mechanics after the firing of a droplet. For the enabling of higher jetting frequencies this is not sufficient. If the complete trial length is used to actively damp the fluid-mechanics, the increase of the jetting frequency is not possible directly since the actuation signal still uses the whole trial length. A solution is to restrict the actuation time as well. This can be incorporated nicely into the ILC design procedure.[3,16] Another method to circumvent the restriction of the actuation time is the following. The actuation signals that overlap can be added up and provided as input to the system. After all, for a truly linear system the superposition principle is valid. For the higher jetting frequencies, it is not possible to further reduce the actuation time and therefore one has to resort to this latter technique.

Experimental Results and Discussion

The designed ILC controller is implemented on an experimental setup. The reference trajectory is depicted in Fig. 5 along with the sensor signal resulting from a standard trapezoidal and the learned ILC pulse. The accompanying actuation pulses are shown in Fig. 6. Note that the actuation window is restricted to the first 60 μs.

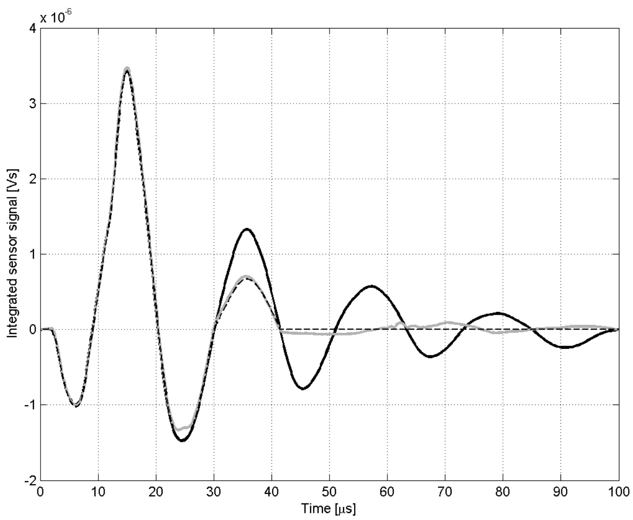

Figure 5. Integrated sensor signal; without ILC (black), with ILC (gray), and reference trajectory (black dotted)

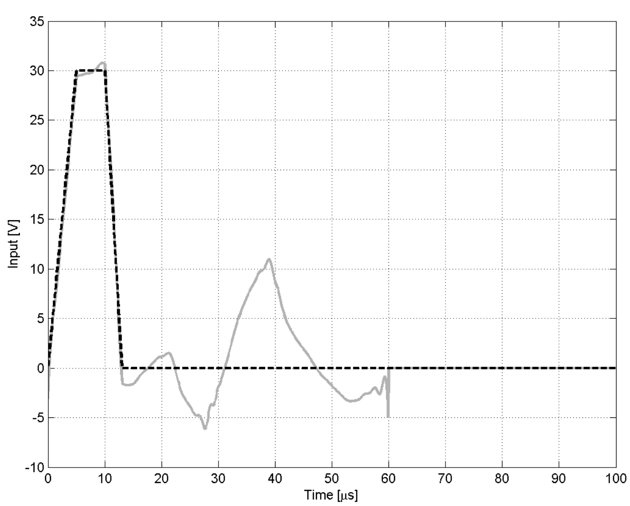

Figure 6. Actuation pulse; standard trapezoidal (black dotted) and ILC pulse (gray)

Based on Fig. 5, the conclusion is drawn that the reference trajectory is attained. As discussed, the first part of reference trajectory up to the firing of a droplet is the same as is realized by the standard trapezoidal pulse. Consequently, it is not surprisingly that the learned ILC pulse resembles the standard trapezoidal pulse for the first part. After that, the ILC controller adjusts the actuation pulse such that the fluid-mechanics follow the desired trajectory, in presence of the restriction concerning the actuation time. The resulting actuation pulses are depicted in Fig. 6. The peaks around 60 μs can be suppressed by additional weightings. Finally, to show that ILC enables higher jetting frequencies, the dependence of droplet speed on the jetting frequency is shown in Fig. 7. As can be seen, the variations in droplet speed are reduced considerably.

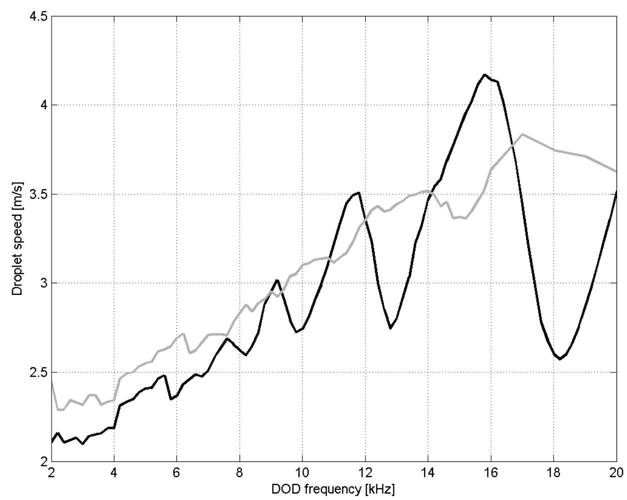

Figure 7. Drop-on-Demand curve; standard trapezoidal (black) and ILC pulse (gray)

Conclusions and Recommendations

In this paper, it has been shown that ILC is suitable control strategy to bring the residual vibrations in an inkjet channel to a rest without influencing the droplet formation. Consequently, the jetting frequency can be increased. Also, it was demonstrated that experimental modeling provides a model of the printhead dynamics that is accurate enough for ILC. Furthermore, the particular choice for the lifted setting for the design of an ILC controller was proven crucial due to the presence of separate actuation and observation windows. Finally, experimental results showed the practical applicability of the proposed control strategy.

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. Also, the influence of the specific sensor location in combination with control goals in mind is further investigated into.

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Author Biography

Matthijs Groot Wassink (1978) received his MSc. degree in mechanical engineering from Delft University of Technology, the Netherlands, in 2002. For his research on 'Linear Parameter Varying Control for a Wafer Stage' he was awarded the Unilever Research Prize. He worked as research engineer for Philips Center for Industrial Technology in Eindhoven, the Netherlands. Currently, he conducts his PhD research at Delft University of Technology in close collaboration with Océ-Technologies B.V. in Venlo, the Netherlands.