Performance Improvement of a Drop-on-Demand Inkjet Printhead: a Feedforward Control Based Approach

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Abstract

The printing quality delivered by a Drop-on-Demand (DoD) inkjet printhead is mainly limited due to residual oscillations in the ink channel. The maximal jetting frequency of a DoD inkjet printhead can be increased by quickly damping the residual oscillations and by bringing in this way the ink-channel to rest after jetting an ink drop. The inkjet channel model is generally subjected to parametric uncertainty. This paper proposes a robust optimization-based method to design the input actuation waveform for the piezo actuator in order to improve the damping of the residual oscillations in the presence of parametric uncertainties in the ink-channel model. Experimental results are presented to show the efficacy of the proposed method.

Introduction

The ability of inkjet technology to deposit materials with diverse chemical and physical properties has made it an important technology for both industry and home use. Apart from conventional document printing, the inkjet technology has been successfully applied in the areas of electronics, mechanical engineering and life sciences [13]. This is mainly thanks to the low operational costs of the technology. Typically, a drop-on-demand (DoD) inkjet printhead consists of several ink channels in parallel. Each channel is provided with a piezo-actuator, which on application of a voltage pulse can generate pressure oscillations inside the ink channel. These pressure oscillations push the ink drop out of the nozzle. A detailed description of the droplet jetting process can be found in [11]. The print quality delivered by an inkjet printhead depends on the properties of the jetted drop, i.e., the drop velocity, the jetting direction and the drop volume. To meet the challenging performance requirements posed by new applications, these drop properties have to be tightly controlled.

The performance of the inkjet printhead is mainly limited due to the *residual pressure oscillations*. The actuation pulses are designed to provide an ink drop of a specified volume and velocity under the assumption that the ink channel is in steady state. Once the ink drop is jetted, the pressure oscillations inside the ink channel take several micro-seconds to decay. If the next ink drop is jetted before the residual pressure oscillations settle, the resulting drop properties will be different from the ones of the previous drop. Therefore, at a high jetting frequency, drops will be jetted before the oscillations in the ink channel have completely disappeared and these residual oscillations will influence the drop velocity. This can degrade the printhead performance, since a printhead has to jet drops with a constant velocity at different frequencies. Given this fact, an important characteristic is the so-called DoD curve which represents the ink drop velocity as a function of the jetting frequency (which is also called the DoD frequency). Ideally, the DoD curve must be flat. However, for the above reasons, this DoD curve is far from flat in practice. Our goal in this paper is to flatten the DoD curve by redesigning the piezo actuation pulse.

In the literature, we can find methods based on exhaustive studies [1, 2, 10, 5, 4] and experimental analysis [9, 8] to design the piezo actuation pulse. Unlike the previous approaches we will tackle the operational issues of the DoD inkjet printhead with a systems and control approach. This is a model-based approach and we need a discrete-time model $H(q)$ relating the piezo input voltage (i.e., the input u) to the meniscus velocity (i.e., the output y). The meniscus is an interface between the ink and air. We consider this particular model since it is well known that the velocity of the meniscus is a good measure of the pressure in the ink channel [3, 1]. Consequently, reducing the residual oscillations of the meniscus velocity is equivalent to reducing the residual pressure oscillations in the ink channel.

Mainly due to the limitations of the driving electronics, the optimal input cannot be computed using a feedback controller, but must be computed off-line based on the model $H(q)$ (feedforward control). A feedforward controller using iterative learning algorithm (ILC) is proposed in [11]. However, the main drawback of the approach in [11] is that it is not possible to put a-priori constraints on the shape of the optimal pulse while such constraints are generally present in practice. Indeed, the driving electronics are generally only able to generate trapezoidal shapes for the piezo actuation input. In our earlier work [6] we have presented an optimization-based approach to deal with such shape constraints. In [6] it is proposed to parameterize the class of piezo input satisfying these shape constraints and to determine the optimal input within this class using an optimization-based approach. The possible inputs are parameterized as $u(k,\theta)$ with θ a parameter vector and k the discrete time index. Then a template $y_{\text{ref}}(k)$ is designed for the desired meniscus velocity, i.e., a the meniscus velocity profile with fast decaying residual oscillations. Based on this template $y_{\text{ref}}(k)$ and the transfer function $H(q)$ an optimal actuation pulse $u(t,\theta_{\text{opt}})$ is determined as the one minimizing the norm of the tracking error $e(k) = y_{\text{ref}}(k) - y(k)$. It is shown in [6] that the optimal actuation pulse $u(t,\theta_{\text{opt}})$ designed in this manner using the nominal model $H(q)$ improves the performance of the inkjet printhead compared to the standard trapezoidal actuation. However, the DoD-curve with the optimal pulse $u(t,\theta_{\text{opt}})$ is not completely flat. Reason for this could be that the optimization-based method [6] is a feedforward control strategy and hence, it is highly sensitive to model mismatch.

Experimental investigation suggested that the dynamical model $H(q)$ from the piezo input to the meniscus velocity obtained at different DoD frequencies will not be the same. In [7], we present a very compact uncertainty model Δ such that the uncertain model $H(q,\Delta)$ encompasses the set of dynamical models obtained at various operating DoD frequencies. One can think of designing several optimal actuation pulses, one for every possible operating DoD frequency. In practice, this solution to make the DoD curve flat is difficult to implement due to the hardware limitations. These limitations demand a single actuation pulse to be designed such that its performance is fairly good over the operating range of the DoD frequencies. Therefore, we have extended the optimization-based approach to design a robust actuation pulse. The robust actuation pulse can be obtained by minimizing the sum of squared error with the uncertain inkjet system $H(q,\Delta)$. This paper summarizes the results in [6] and [7].

System description and modeling

Several analytic and numerical models are available for the inkjet channel dynamics. For control applications, one prefers a simple model with sufficient accuracy. Therefore, we select a simplified discrete-time model $H(q)$ based on the 'narrow-gap model' [12]. We know that higher-order modes in the meniscus velocity do not contribute significantly to the drop formation process [3]. Hence, these higher-order modes are neglected in $H(q)$. The discrete-time model $H(q)$ describes the dynamics from the piezo input voltage u to the meniscus velocity y. The transfer function $H(q)$ is given as follows

$$H(q) = g\left(\frac{q^2+b_1q+b_2}{q^2+a_1q+a_2}\right)\left(\frac{q^2+b_3q+b_4}{q^2+a_3q+a_4}\right) \tag{1}$$

where q is the forward shift operator. Figure 1 shows the frequency response of the above fourth order transfer function $H(q)$ with the solid blue line.

As discussed in the introduction, at different DoD frequencies, the dynamics from the piezo input to the meniscus velocity $H(q)$ will be not be the same. This may be due to the unmodeled refill dynamics or due to nonlinear effects in the drop formation process. In order to investigate this phenomenon, we have used experimental identification. It is very difficult to experimentally measure the meniscus position and the meniscus velocity while jetting an ink droplet. However, the piezoelectric crystal can be simultaneously used as an actuator and as a sensor. Therefore, we have identified a dynamical system from the piezo input to the piezo-sensor output (which is proportional to the derivative of the ink-channel pressure) at a fixed DoD frequency. We have done several such experiments at various fixed DoD frequencies in the operating range of the inkjet printhead. The details of the identification experiments are omitted in this paper due to lack of space.

It is observed that the first resonant mode of the inkjet system varies a lot compared to the second resonant mode. Using this information, it can be found that for the first resonant mode of $H(q)$, the resonance frequency ω_{n1} variation is approximately in the interval $[-7\% \ +7\%]$ and the damping ζ_{n1} variation is approximately in the interval $[-70\% \ +30\%]$. The variation in the second resonant mode is relatively smaller compared to the first one. Hence, in order to obtain a simpler and more compact uncertainty description we assume that only the first resonant mode is uncertain. This is a valid assumption since the first mode greatly influences the ink drop properties [3] compared to the second mode. The details on the mapping of the uncertainty on the properties of the resonant mode to the coefficients of the transfer function (1) can be found in [7]. Due to the uncertain first resonant mode, the coefficients of the T.F. (1), a_1 and a_2 are subjected to uncertainty Δ. The uncertainty $\Delta = [\Delta^{(1)} \ \ \Delta^{(2)}]^T$ perturbs the coefficients a_1 and a_2 in the following manner:

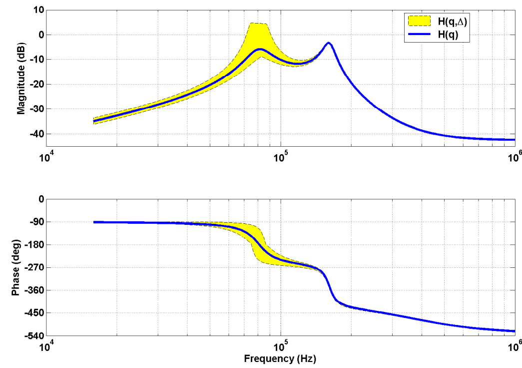

Figure 1. Frequency response of the transfer function model $H(q)$

$$a_1(\Delta) = a_{1,\text{nom}}(1+\Delta^{(1)}) \tag{2}$$

$$a_2(\Delta) = a_{2,\text{nom}}(1+\Delta^{(2)}), \tag{3}$$

where $a_{1,\text{nom}}$ and $a_{2,\text{nom}}$ are the nominal values of the coefficients a_1 and a_2. This means that the uncertainty Δ on the coefficients a_1 and a_2 lie in the set $\mathfrak{D}$ given in the Figure 2. Now, the set of dynamical models obtained at various operating DoD frequencies can be represented by the uncertain inkjet system $H(q,\Delta), \Delta \in \mathfrak{D}$. The frequency response of the uncertain inkjet system which is represented by $H(q,\Delta)$ is shown by yellow shaded area in Figure 1.

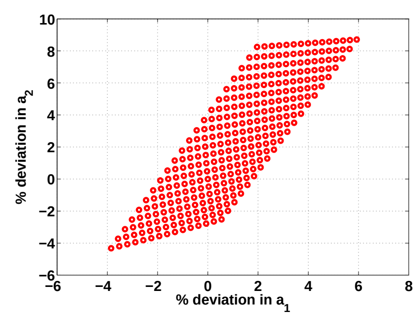

Figure 2. Parametric uncertainty in % of the nominal value

Feedforward control design

In [7], we have discussed in detail the limitations of the control system which restrict us to use feedforward strategy to control the inkjet system. The driving electronics limit the range of the actuation pulses that can be generated in practice. The only possible choice of the actuation pulse is the trapezoidal waveform. Figure 3 shows the parametrization of the actuation pulse as proposed in [7].

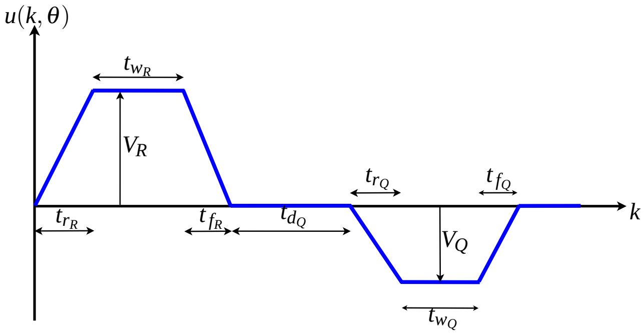

Figure 3. *Proposed piezo actuation pulse.*

The actuation signal $u(k,\theta)$ then consists of a positive trapezoidal pulse (called resonating pulse), which is responsible for jetting the ink drop, followed by the negative trapezoidal pulse (called the quenching pulse) which damps the residual oscillations. Now, the actuation pulse can be characterized by the rise time (t_r), the dwell time (t_w), the fall time (t_f) and the amplitude (V) of both the resonating and the quenching pulse. The time interval between the resonating pulse and the quenching pulse is t_{d_Q}. Thus, an actuation pulse $u(k,\theta)$ is defined by the parameter vector $\theta = [t_{r_R}\ t_{w_R}\ t_{f_R}\ V_R\ t_{d_Q}\ t_{r_Q}\ t_{w_Q}\ t_{f_Q}\ V_Q]^T$. As opposed to the approaches in [8], the optimal parameter vector of the actuation pulse can be determined using a systematic (optimization-based) approach as shown in the sequel.

Control Objective

In order to define the optimization problem leading to the optimal parameter vector θ_{opt}, we need a template $y_{\text{ref}}(k)$ for the desired meniscus velocity. In this section we describe the procedure to construct the desired meniscus velocity trajectory $y_{ref}(k)$ using the transfer function model $H(q)$ and the standard pulse.

For the considered inkjet printhead, the standard pulse is represented in Figure 4 and corresponds to a parameter vector $\theta_{\text{std}} = [1.5\ \ 2.5\ \ 1.5\ \ 25\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]^T$ when using the parametrization in Figure 3. This standard pulse allows to jet one drop at the desired velocity, but the residual oscillation generated by this standard pulse perturbs the subsequent drops. Such a behavior can be observed in Figure 4 (dashed line) where we represent the response of the model $H(q)$ to the standard pulse. As shown in Figure 4, we can characterize the meniscus velocity response $y(k)$ in two parts. Part A of the response $y(k)$ allows the drop to be jetted at the desired drop velocity. A procedure is described in [3] to predict the properties of the jetted drop using Part A of the meniscus velocity profile. Since we want to jet the ink drop at the desired ink-drop velocity, the desired meniscus velocity $y_{\text{ref}}(k)$ should be the same as $y(k)$ in Part A. Part B of the response $y(k)$ represents the residual oscillations. This is an undesired behavior, since, the residual oscillations perturb the subsequent drops. Therefore, in Part B, we force the desired meniscus velocity $y_{\text{ref}}(k)$ to zero. This means fast decaying residual oscillations. This template $y_{ref}(k)$ is represented by the solid line in Figure 4.

Thus, the desired meniscus velocity $y_{\text{ref}}(k)$ is a meniscus velocity profile to jet an ink drop with the desired drop-velocity and fast decaying residual oscillations. If the actuation pulse is designed in such a way that the meniscus velocity $y(k)$ follows the reference trajectory $y_{\text{ref}}(k)$, then the channel will come to rest very quickly after jetting the ink drop. This will create the condition to

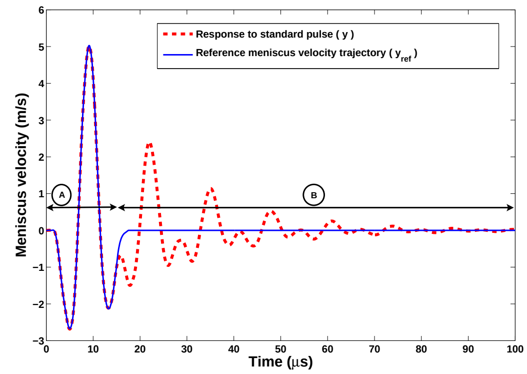

Figure 4. *Reference meniscus velocity trajectory.*

jet the ink drops at higher jetting frequencies.

Now, we present a brief summary of the optimization-based method [6] to design the optimal actuation pulse using the nominal model $H(q)$ of the inkjet system. In sequel we will present extension of this method to design the robust pulse.

Optimal actuation pulse design

The optimal input is the trapezoidal input $u(k,\theta)$ which minimizes the difference between the reference trajectory $y_{\text{ref}}(k)$ and the meniscus velocity $y(k,u(k,\theta)) = H(q)u(k,\theta)$. More precisely, we can define the objective function as the following sum of square errors

$$J_{\text{opt}}(\theta) = \sum_{k=0}^{N} \Big(y_{\text{ref}}(k) - H(q)u(k,\theta) \Big)^2 \tag{4}$$

where $N = \frac{T}{T_s}$, T_s is sampling time, T is chosen equal to $100\,\mu$s, $H(q)$ is the nominal discrete-time model from piezo input to the meniscus velocity, q is here the forward shift operator and $u(k,\theta)$ is the proposed actuation pulse parameterized by the parameter vector θ .

Thus, the optimal actuation pulse parameter θ_{opt} is the parameter vector θ solving the following optimization problem

$$\min_{\theta} J_{\text{opt}}(\theta), \quad \text{subject to} \quad \theta_{LB} \leq \theta \leq \theta_{UB}, \tag{5}$$

where, θ_{LB} and θ_{UB} are the vectors containing the lower and the upper bounds on each element of the parameter vector θ.

This is a nonlinear optimization problem and can be solved offline using standard optimization algorithms. For this purpose, we use gradient-based optimization algorithm of the MATLAB, more specifically the function `fmincon`. Gradient-based optimization is an iterative method. The gradient of $J_{\text{opt}}(\theta)$ is computed numerically around the current value of θ and then the parameter θ is updated in the gradient direction.

In the next section we will see this method helps to improve the DoD-curve compared to the standard pulse, but does not completely faltten the DoD-curve. This could be because it uses only the nominal model $H(q)$ for the actuation pulse design and does not takes into account the multiple dynamical models at various operating DoD frequencies. We will see later that the robustness of the actuation pulse can be improved if we consider this set of multiple dynamical models $H(q,\Delta)$ for the actuation pulse design.

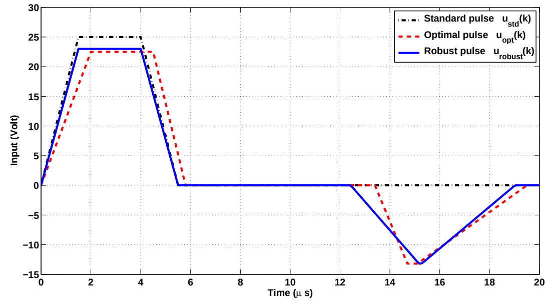

Figure 5. *Actuation pulses*

Robust actuation pulse design

In the section of system description and modeling, we have seen that the multiple models obtained at different DoD frequencies can be represented by $H(q,\Delta)$, i.e. the nominal inkjet model with a compact polytopic uncertainty $\Delta \in \mathfrak{D}$. In the design of the optimal pulse, the performance index (4) for the actuation pulse is defined as the sum of square of the tracking error for the nominal model $H(q)$. Now, we have the set of multiple models represented by the uncertain inkjet system $H(q,\Delta)$ which is perturbed by the uncertainty $\Delta \in \mathfrak{D}$. Therefore, we should design a robust actuation pulse whose average performance is good over the polytopic uncertainty $\mathfrak{D}$, rather than obtaining an optimal actuation pulse whose performance is only good for the nominal inkjet system $H(q)$. As the dimension of the parameter space of Δ is only 2, we can easily grid the parametric uncertainty $\mathfrak{D}$. Let the set $\mathscr{S}$ be the grid on the parametric uncertainty $\mathfrak{D}$, defined as

$$\mathscr{S} = \{\Delta^i, i = 1, ..., m, \mid \Delta^i \in \mathfrak{D}\}$$

For a given parameter vector θ, we define the robust performance index $J_{\text{rob}}(\theta)$ as the worst-case sum of squared error computed at each of the m grid elements, i.e.:

$$J_{\text{rob}}(\theta) = \max_{\Delta^i \in \mathscr{S}} \sum_{k=0}^{N} \Big(y_{\text{ref}}(k) - H(q,\Delta^i)u(k,\theta)\Big)^2. \tag{6}$$

Now, the constrained robust actuation pulse parameter is thus the solution θ_{robust} of the following optimization problem

$$\min_{\theta} J_{\text{rob}}(\theta), \quad \text{subject to} \quad \theta_{LB} \le \theta \le \theta_{UB}, \tag{7}$$

where, θ_{LB} and θ_{UB} are the vectors containing the lower and the upper bounds on each element of the parameter vector θ.

This is a nonlinear optimization problem and can be solved offline using standard optimization algorithms similar to the problem (5).

Experimental Results

In this section, we present experimental results to show the improvements in the drop consistency with the optimal actuation pulse and the robust actuation pulse. In order to obtain the optimal actuation pulse $u_{\text{opt}}(k) = u(k,\theta_{\text{opt}})$ we have solved the nonlinear optimization problem (5) using the command `fmincon` from the optimization toolbox of MATLAB. This optimal pulse $u_{\text{opt}}(k)$ is shown in Figure 5 by the dashed red line. The experimental setup is equipped with a CCD camera which can capture the images of jetted drops at an interval of 10μs. The details about the experimental setup, such as the camera, the microscopic lens etc

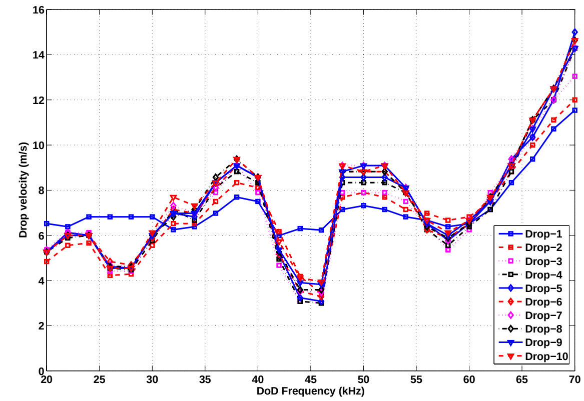

Figure 6. *Experimental DoD curve with the standard pulse $u_{std}(k)$.*

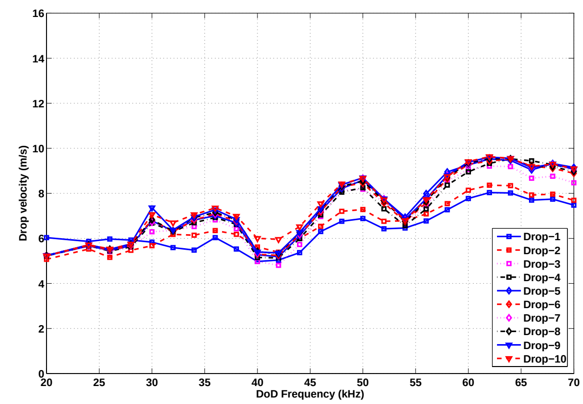

Figure 7. *Experimental DoD curve with the optimal actuation pulse $u_{opt}(k)$.*

can be found in [12]. In each experiment we have jetted 10 ink drops from the inkjet channel at a fixed DoD frequency using the standard pulse $u_{\text{std}}(k)$ and the optimal pulse $u_{\text{opt}}(k)$. These images are processed further to compute velocities of the jetted ink drops. We have carried out several such experiments for different DoD frequencies ranging from 20 kHz to 70 kHz with the step of 2 kHz. The drop velocities of each of the 10 drops are shown in Figures 6 and 7 as a function of the DoD frequency (DoD curve). Figure 6 is obtained when the standard pulse $u_{\text{std}}(k)$ is used and Figure 7 shows the results when the optimal pulse $u_{\text{opt}}(k)$ is used. For the standard pulse, it can be seen that the maximum drop velocity variation is 12ms^{-1} due to the undamped residual oscillations (see the DoD-curve in Figure 6). The optimal pulse $u_{\text{opt}}(k)$, designed using the nominal inkjet model $H(q)$, consists of a negative trapezoidal pulse to damp the residual oscillations. Due to this, the maximum drop velocity variation in the DoD-curve with $u_{\text{opt}}(k)$ is reduced to 4.5ms^{-1}.

We can see considerable improvement in the DoD-curve with the optimal pulse $u_{\text{opt}}(k)$ compared to the standard pulse $u_{\text{std}}(k)$. However, the DoD-curve is not completely flat. This is because the optimal pulse is designed using only the nominal model $H(q)$ of the inkjet system, which is not the center of uncertainty set $\mathfrak{D}$. Therefore, the performance of the optimal pulse will be degraded when the dynamics is changed at different operating DoD frequencies. Therefore, we design the robust pulse using the

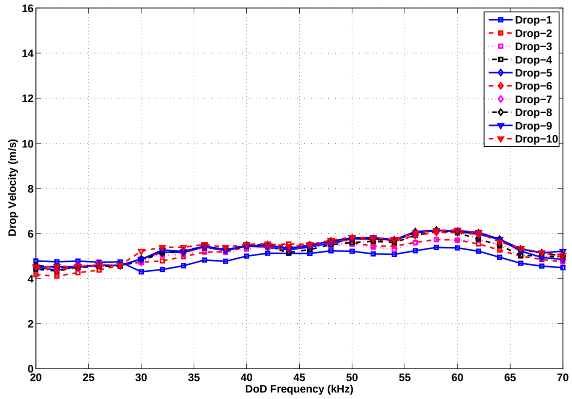

Figure 8. *Experimental DoD curve with the robust actuation pulse* $u_{robust}(k)$.

uncertain inkjet system $H(q,\Delta)$, which represents the set of dynamical models obtained at different operating DoD frequencies. The nonlinear optimization problem (7) is solved by using the command `fmincon` from the optimization toolbox of MATLAB. The robust pulse pulse $u_{\text{robust}}(k) = u(k, \theta_{\text{robust}})$ designed in such a manner is shown in Figure 5 by the solid blue line. We have done similar experiments as mentioned earlier with the robust pulse and we have obtained the DoD-curve, shown in Figure 8. Since the robust pulse is designed to give a good average performance over the set of the dynamical models represented by $H(q,\Delta)$ it delivers better results than the optimal pulse. Now, the drop velocity variation is even less than 2ms^{-1} (see the DoD-curve in Figure 8).

The overall improvement in the velocity consistency achieved using the optimal pulse and the robust pulse has far-reaching consequences for the print quality. This is because of the proximity of the inkjet printhead to the printing paper.

Conclusion

The proposed feedforward control law is an extension of the optimization-based method, which can provide best results if the actual system dynamics does not deviate from the model used in the design. We have observed that the inkjet system dynamics at different DoD frequencies will not be the same. Therefore, we have proposed represent this set of dynamical models by a compact parametric uncertainty $\Delta \in \mathfrak{D}$ on the nominal model of the inkjet system, i.e. $H(q,\Delta)$. In order to damp the residual oscillations in the presence of this parametric uncertainty, the optimization-based is extended to design the robust actuation pulse which minimizes the worst-case squared tracking error. Experimental results have demonstrated that a considerable improvement in the ink drop consistency can be achieved with the proposed robust pulse. Applications of the proposed method to multi-channel control will be investigated in the future.

Acknowledgments

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