Driving Waveforms to Reduce Voltage Requirement of Inkjets

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Abstract

A drop is ejected from an inkjet by building a pressure upstream of the aperture. The pressure is built by applying a voltage waveform to some type of driver. In this study, the maximum required voltage to operate an inkjet was reduced by building the required pressure over multiple oscillations of the driver, prior to actual drop ejection. Hypothetically, multiple prepulses could be used, limited by the total period between drops, to be fired by the printer. When a prepulse was timed such that the energy added constructively with the main, firing, pulse, the required voltage of the firing pulse was reduced. Conversely, if the energy added destructively, the required voltage increased. The amplitude of the prepulse was limited by the following constraints: (1) it could not force air to be ingested into the inkjet; (2) it could not add enough energy to eject a drop itself or push the meniscus over the edge of the nozzle. In a typical situation, the prepulse reduced the required driving voltage by more than 20%. This improvement can be used in a few ways: (1) The drive voltage can be reduced (as discussed); or (2) a smaller driver can be used for the same voltage, allowing tighter packing of jets; or (3) an inkjet can be driven at a frequency further from its resonant frequency, which should reduce sensitivity to manufacturing variations.

Nomenclature

F_0	Frequency of the bulk mode of the inkjet
F_1	Frequency of the first standing wave mode of the inkjet
F_P	Characteristic frequency of the half sine wave prepulse
Time_fire	Duration of the drop-firing part of the waveform
V_fire	Maximum voltage of the drop-firing part of the waveform
V_P	Maximum voltage of the prepulse

Introduction

Pressure is generated upstream of an aperture, to fire a drop from an inkjet. The mechanism by which pressure is created varies; bubble jets are obviously different than PZTs. In the inkjet, tested in this study, the pressure was created by deflecting a diaphragm, using a PZT driver (Figure 1). But, however it is accomplished, an electrical signal (waveform) is converted into a pressure at the aperture.

In general, a waveform with a higher voltage would result in a larger drop mass and faster drop velocity. However, if the effectiveness of the inkjet, for a given voltage, could be improved, there would be advantages: The voltage, required to generate a drop, could be reduced. Or, smaller drivers could be used to generate drops, allowing tighter packing of jets. Or, an inkjet could be operated farther from its resonant frequencies, which would likely reduce sensitivity to manufacturing variations.

To improve the effectiveness of the inkjet we should first consider where the electrical energy goes. Some of the energy is useful; it ejects the drop. It would be nice if all of the electrical energy could be used to eject a drop, with no waste. Of course, we know that does not happen. Some of the input energy is lost while a drop is being fired, either by damping or by transmission to another part of the printhead. Also, some extra energy will be left in the inkjet after a drop has fired. After a drop has fired, the fluid in the inkjet will oscillate, due to that extra energy. Given sufficient time, this residual energy will be damped or transmitted, and the inkjet will return to its quiescent state. However, if the subsequent drop is fired before the energy has had time to dissipate, that drop may be bigger, smaller, faster, slower, or the same as the previous drop, depending whether the residual energy adds constructively, destructively or neutrally. This is an effect we have observed. But, instead of just observing it, perhaps we can use it to our advantage, to improve the effectiveness of an inkjet. Perhaps we can purposely introduce extra energy, in such a way that a drop would be bigger and faster.

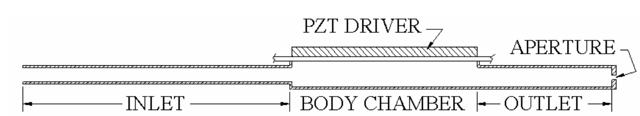

Figure 1. Sketch of PZT-driven inkjet

Thus, the hypothesis of the present study was the following: The required maximum voltage of a driving waveform could be reduced by introducing energy, via an extra electrical pulse, preceding the main, firing waveform.

In general, the energy of this prepulse can add constructively or destructively with the main firing waveform. To actually reduce the required voltage, the energy of the prepulse would need to add constructively. In addition, the greatest effect can be experienced if energy is added near the frequency of one of the dynamic modes of the inkjet.

Method

This hypothesis was tested using Xerox Phaser 8400 inkjets. As sketched in Figure 1, the inkjet was driven by a PZT, attached to a diaphragm. The fluid path consisted of an inlet, a body chamber, an outlet and an aperture. The inlet connected the inkjet with the manifold system. The body chamber had the PZT driver on one side. The outlet connected the body chamber with the aperture. Finally, aperture was the site drops of ejection. The polarity of the PZT was such that a positive voltage increased the volume of the body chamber (i.e. pulled the meniscus inward). Similarly, a negative voltage decreased the volume of the body chamber (i.e. pushed the meniscus outward).

This type of inkjet had two dominant fluidic resonances. The lowest frequency was the bulk mode (F_0) in which the inlet and aperture acted as fluidic resisters and inductors, while the body chamber, outlet and driver acted as a fluidic capacitor. The next mode (F_1) was a standing wave in the combined lengths of the outlet and body. F_1 was several times larger than F_0. The modes of the inkjet (F_0 and F_1) were measured using an impedance analyzer, under linear conditions; the voltage applied was much less than would be required to fire a drop. This means the meniscus moved very little when measuring F_0 and F_1. A description of the analysis of these modes is given in References 1 and 2. Results of this work were expressed relative to the one or both of these modes.

Naturally, prior to considering a prepulse, a main firing waveform was needed, to which the prepulse would be applied. In this study, the drop was fired by waveform, made up of two half-sine waves; the positive pulse was slightly longer than the negative pulse (see Figures 2 and 3). Time_fire was the duration of the firing waveform and V_fire was the maximum voltage of the firing waveform. V_fire, was changed as described in the results below; Time_fire, was held constant throughout the study.

When developing a prepulse, it was expected that the voltage would be less than that of the firing pulse (otherwise the prepulse would become the highest voltage and defeat the purpose of reducing the voltage of the firing pulse). However, it was also expected that, in order to make a difference, a significant prepulse voltage would need to be applied, relative to the voltage required to fire a drop. Of course, when a significant voltage was applied, the meniscus would have moved significantly within the aperture. As meniscus moved, the fluidic inductance and resistance of the aperture would have been changed. The result of this motion is that, when the meniscus was being pulled into the inkjet, the response timescale of the inkjet was decreased; so the inkjet would respond most to energy with a characteristic frequency higher than predicted by the linear measurement. Similarly, when the meniscus was pushed outward, the jet would likely respond most to a lower frequency than the linear measurement. The fact is, when a jet was firing and when the prepulse was applied, the dynamics were non-linear. No attempt was made here to quantify this non-linearity analytically. The best frequencies were determined experimentally, as described below.

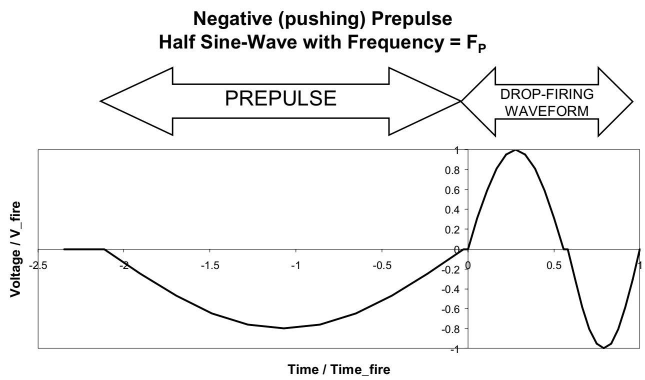

Figure 2. Negative prepulse. The duration and amplitude of the prepulse was varied for optimization.

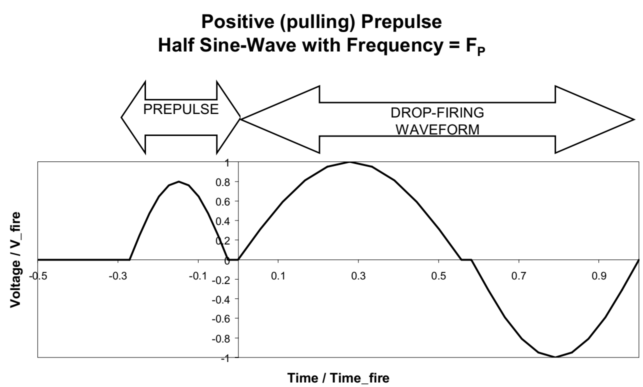

Figure 3. Positive prepulse. The duration and amplitude of the prepulse was varied for optimization

Two families of prepulses were considered: negative (Figure 2) and positive (Figure 3). Each prepulse was a half-sine wave, with a frequency of F_P and maximum voltage V_P. Both F_P and V_P were varied in an effort to improve the effectiveness of the firing waveform.

The drop velocity was used to quantify the effectiveness of the waveform in producing a drop. Obviously, when V_fire was changed, both the drop mass and the drop velocity were changed. Drop velocity was selected as the metric, because of its convenience of measurement and good repeatability. The repeatability error for the velocity, of an individual inkjet, had a standard deviation of 0.31%. Each data point shown below is the average of more than 1000 individual inkjet measurements. This averaging reduced the standard deviation of the repeatability error, for velocity, to

0.16% (which was not a big improvement, given the number of samples). The drop mass repeatability had a standard deviation of 0.44%, even after averaging more than 1000 inkjets.

Results and Discussion

The first prepulse, which was considered, had a positive voltage (as shown in Figure 3). Positive prepulses added energy constructively at timescales near the first standing mode of the inkjet (F_1). Recall, positive voltages pulled the meniscus into the jet; so, it was expected that energy would be most effectively added at a frequency higher than the linear frequency. This was, in fact, the case, as shown in Figure 4. The velocity was increased most using a prepulse frequency of $1.3*F_1$. At that frequency, the velocity was increased by 50%, for a prepulse voltage of +0.8*V_fire. The velocity dropped off more quickly below the optimal frequency than above the optimal frequency. Below about half of F_1, energy added destructively, and the velocity was actually reduced by applying the prepulse.

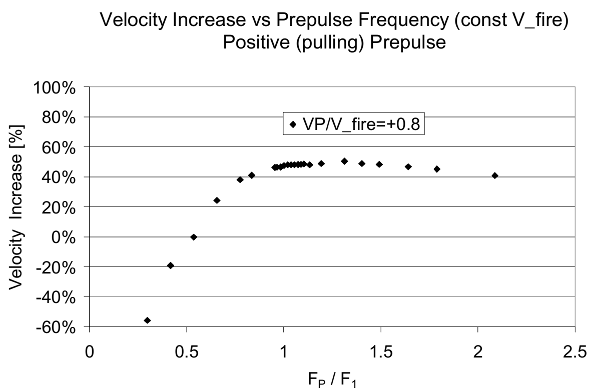

Figure 4 The ability of a positive prepulse to increase the velocity of a drop.

Prepulses with negative voltages were considered next. The energy from negative prepulses added constructively to the firing waveform at relatively longer timescales than did positive prepulses. Negative prepulses seemed to be more closely associated with the bulk mode (F_0) than the first standing mode (F_1). As a result, the frequencies of the negative prepulses are shown relative to the bulk mode frequency. Figure 5 shows how effective negative prepulses were, to increase drop velocity, holding the firing voltage (V_fire) constant. A negative prepulse pushed the meniscus outward. So, as expected, the most effective frequency for a negative prepulse was below the linear frequency. For a prepulse voltage of –0.8*V_fire, the most effective prepulse frequency was $0.44*F_0$. It resulted in an increase of drop velocity of 74%.

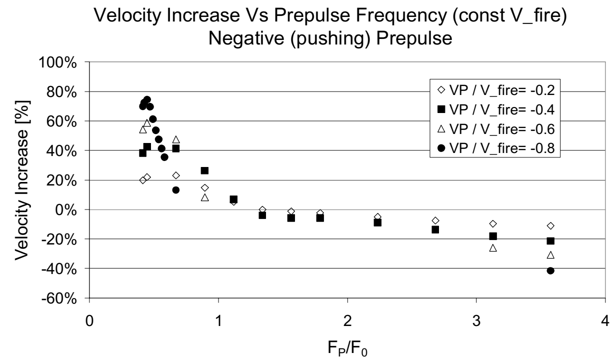

Figure 5. The ability of a negative prepulse to increase the velocity of a drop.

There are several data points missing, at higher prepulse amplitudes, near the middle frequencies on Figure 5. Under those conditions, the prepulse disrupted the actual firing of the drops to such an extent that drop velocities could not be measured. Interestingly, the disruption was most severe at frequencies where the velocity was least affected, either constructively or destructively (based on the existing data at lower prepulse amplitudes).

The dropoff of velocity with frequency was not consistent among the different voltage ratios. Although the largest amplitude prepulse increased the drop velocity the most at the peak frequency ($0.44*F_0$), it also had the sharpest peak. Its velocity dropped off fastest as the frequency was changed from the peak. As a result, there were frequencies at which lower prepulse amplitudes resulted in more improvement to drop velocities. This was likely caused by two factors, which are related: the jet dynamics were not linear at these voltages, and a half-sine wave was likely not the best shape to constructively add energy to this inkjet.

Although this was a good first step, the goal was not to maximize velocity; the goal was to decrease the required voltage. So, the next step was to quantify the voltage reduction. The best frequencies for positive and negative prepulses, from the velocity data above, were used. For various prepulse amplitudes, the voltage required to achieve the original drop velocity was determined. Figure 6 shows the results. For a given amplitude, the negative prepulse was more effective at reducing the voltage requirement than was the positive prepulse. The negative prepulse reduced the voltage by 21%, while the positive prepulse reduced the voltage by 14%. However, depending on the situation, one might still choose to use the positive prepulse. The total driving waveform was of a shorter duration using a positive prepulse; and, unlike the negative pulse, the positive pulse was not disruptive to drop firing near frequencies where the velocity was unaffected.

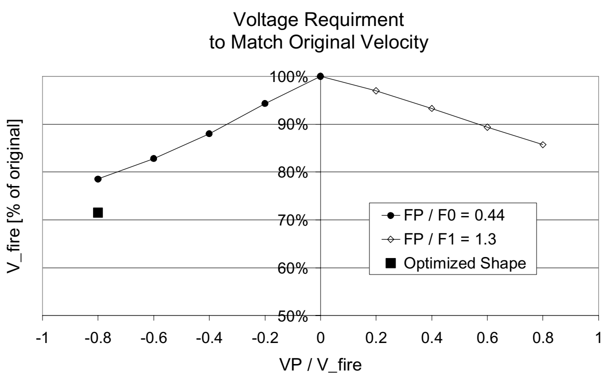

Figure 6. The voltage requirement was reduced by applying a prepulse, before the main firing waveform.

As mentioned above, a half-sine wave was likely not the best shape to add energy constructively to this inkjet. So, the prepulse shape was altered to reduce voltage even further. Since the negative half-sine wave was more effective than the positive half-sine wave, the negative prepulse was the basis for optimization. The waveform shape was distorted until the voltage could not be reduced further, subject to the following constraints: the prepulse could not change sign, the maximum voltage amplitude could not exceed that of the negative half-sine wave (Vp/V_fire = -0.8). The result of the optimization is shown on Figure 7. Note that, although the waveform started the optimization process with rounded sides, it ended with sharp corners. Also, the optimized waveform had a slight delay between the prepulse and the firing waveform. It is possible than even the half-sine wave could have benefited from such a delay. The large trapezoid-shaped portion of the prepulse caused the overwhelming majority of the voltage reduction. The frequency of the large trapezoid was actually closer F_0 than the best half-sine wave. The extra, higher frequency, notches had a small, but measurable, effect on the voltage reduction. They were closer to the frequency of the first standing mode (F_1). The optimized prepulse shape reduced the required firing voltage by 29% (the square symbol on Figure 6).

It is possible that the required voltage could be reduced even further, by using multiple prepulses, perhaps with alternating signs. But, that is beyond the scope of this study. The purpose of this study was to prove the hypothesis, which was done. Due to the non-linear nature of the inkjet, the detailed results would change for different inkjet geometries or even different drop-firing waveforms. But, the same process could be used to optimize a prepulse, as described above. When developing a prepulse, it is important to make sure it is not harmful to the subsequent drop ejection. As we have seen, certain prepulses interfered with drop ejection sufficiently to prevent measurement of velocity. Things to be avoided include the following: The prepulse should not ingest air into the inkjet. The prepulse should not force the meniscus to burst onto the faceplate of the printhead. The prepulse should not, itself, eject a drop. The total duration of the prepulse and drop-firing waveform cannot exceed the time between drop firings.

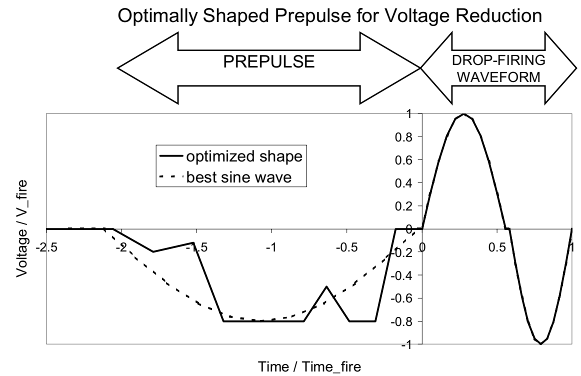

Figure 7. The voltage requirement was reduced even further by changing the shape of the waveform.

Conclusion

As we have seen, prepulses can add energy either constructively or destructively to the firing of an inkjet. The best time scale for a prepulse is affected by whether it is positive (pulling the meniscus inward) or negative (pushing the mensicus outward). For the inkjet considered here, the voltage was reduced by as much as 21% using a negative sine wave, and by as much as 14% using a positive sign wave. By optimizing the shape of the prepulse, the required voltage was reduced by 29%. The optimized shape was much more angular than the original sine wave. A prepulse should be possible for most inkjets, as long as it is developed such that the resulting drop ejection is not adversely affected.

References

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Biography

Douglas Darling received a B.S. in Mechanical Engineering in 1986. Then, he earned his Ph.D. in Mechanical Engineering from the University of Illinois at Urbana-Champaign in 1989. Subsequently, he worked at NASA-Lewis Research Center (currently NASA-Glenn) and Siemens-Westinghouse Power Corporation on unsteady fluid dynamics and acoustics. Since 2000, he has worked at the Xerox Corporation in Wilsonville, Oregon, in solid ink printhead development.