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A Novel Process of Automated Waveform Optimization

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Abstract

In this research project, ImageXpert attempts to combine drop visualization with a methodology for waveform creation into an automated process for designing and optimizing waveforms. Waveforms are an essential, but often mysterious, aspect of inkjet printing that controls the performance of the system. It is important to understand how waveforms work in order to properly design them. In piezoelectric printheads, the waveform is an electrical signal that is applied to the piezoelectric materials, causing them to deform. This deformation, when done with proper rhythm, is the driving force behind the nozzles of the printhead filling and jetting ink. Getting the proper rhythm of ink in the nozzle to ensure consistent, stable jetting is the goal when optimizing a waveform.

The waveform optimization methodology that was used was optimization of the pulse width, then voltage, then pulse spacing while monitoring behavior over a range of frequencies. Using commercially-available systems along with custom scripting, a process for fully automating this optimization was developed. It works by specifying a range for each parameter and automatically sweeping through that range, while capturing images and data at each value. Using this technique, a waveform can be developed or optimized using automation in a fraction of the time spent doing it manually.

Background

Before we can attempt to automate the process of optimizing a waveform, we have to start with the basics and understand how a waveform works. To help explain the purpose of a waveform, let's take a look inside a nozzle chamber of a printhead. The image below, Figure 1, depicts the jetting process known as fill-and-fire, which is quite commonly applied to many different printheads of varied design. In this case, a stack of PZT (a piezoelectric ceramic material) deforms whenever voltage is applied to it, changing the volume of the ink chamber and causing the ink to move within it and eventually eject. The means of applying this voltage to the PZT is the waveform.

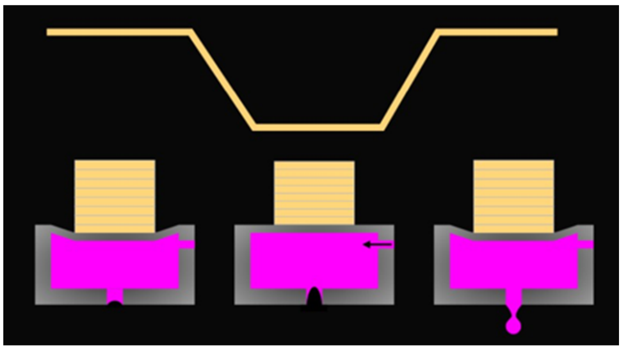

Figure 1. The inkjet fill-and-fire process

In our example, the PZT is extended only when voltage is applied, so there will be no deformation until the printhead is plugged in. Once powered, the printhead maintains a specific voltage, causing the PZT to extend and remain in its non-jetting position (Left). If the voltage is decreased, the PZT retracts and creates an expansion in the chamber, drawing ink into it (Center). To eject a drop, the voltage is returned to its original value, the chamber shrinks, and the excess ink is forced out (Right). This process repeats thousands of times per second.

It is important to note that printheads can be driven by either positive-going or negative-going pulses, depending on how they are manufactured. Whichever way you're used to looking at it, the important waveform timings are the two sloping parts and the hold time, i.e. how long the voltage is kept at that level (high or low) before it returns to the start position. Usually when waveform optimization is discussed, the fundamentals are the optimization of the hold time (or pulse width) and the amplitude / voltage of the pulse.

Procedure

Currently, inkjet waveform optimization is achieved through a combination of prior experience and experimentation. Small adjustments are made to the waveform and the resulting print is inspected for deterioration or improvement. This process was made easier with the invention of dropwatchers, as the behavior of the drops using different waveforms could be more closely analyzed. In either case, the length of this process often depends on the experience of the researcher, who may have learned patterns in the response.

The goal of this research is to produce a faster alternative through machine vision and scripting. If we can simultaneously make adjustments to the waveform and get visual / numerical feedback as to whether the waveform is improved or worsened, much of the experimentation can be automated.

Each individual part of this process can be accomplished with equipment on the market. The development was done using a JetXpert dropwatching system for visual and numerical analysis, a variety of industrial inkjet printheads, Global Inkjet Systems drive electronics, and a MegnaJet Labjet ink supply. A picture of such as setup is shown below.

Figure 2. Example test setup, with JetXpert dropwatcher, Dimatix Samba printhead, and GIS drive electronics

The process involved determining a consistent methodology for waveform development and translating it into a scripted procedure that could be executed automatically. The theory of how to optimize a waveform is explained below for each step in the process, followed by the actual results produced through automation.

The process works by selecting a waveform variable and specifying a range of values to “sweep” through. The system could sweep through values for different parameters including voltage, hold time, rise and fall time, and pulse spacing. The drive electronics would assign the first value to the waveform and begin jetting with that waveform. The JetXpert system would capture an image of the drop and measure its volume and velocity. Once this data was saved, the drive electronics would repeat the process with the next value in the list. Based on these images and data, the user could provide feedback as to which values produced the optimum results. This procedure, when combined with methodology for the correct order of parameters to sweep through, has the potential to systematize the optimization process.

Pulse Timing Basics

If you’ve stood next to a print head while it is printing, you might have been able to hear it “sing”, depending on what frequency was being used. The reason you can hear it is because the actuators produce sound waves. The most important ones for jetting are the ones that get produced in the ink itself, since they define the pressure variation that gives drop ejection.

Because of the presence of an ink with certain mechanical properties, and the fact the sound waves can lose energy as they bounce around, the pressure in the chamber can be described as a damped resonator. Any change in pressure, such as the PZT deforming, will result in a characteristic pressure variation. When the PZT retracts and the chamber increases in volume, the pressure change causes the ink to begin moving back and forth within the chamber.

This energy alone is usually not enough to cause the ink to eject, it just pulls it back to the opposite end of the chamber and bounces off. By using a voltage pulse to reinforce the pressure at the right time, the drop ejection is made more efficient. A drop is ejected when the pressure goes over a critical value due to the preferable timing.

The reason the pulse width is so critical is that if it is too short, or too long, then the waves, pressure, and movement of the PZT will be out of sync. If the ink is not moving the right direction at the time more pressure is added, instead of smoothly adding to the momentum, the momentum might be countered. It is similar to pushing a child on a swing. If you push them at the right time, the momentum is increased and they swing higher. If you push them at the wrong time, they will come to a violent stop. Similarly, if the pulse width is wrong, the resulting jetting, repeated over and over, will be inefficient and unstable.

Since the length of the nozzle chamber is fixed, you might think that the pulse width needed to correctly time the pressure wave is constant for a given printhead. However, the timing is also impacted by the speed of sound for that particular ink. This is why a waveform must be tuned for a particular ink and printhead combination, it is not enough just to have a general waveform for that printhead. Fortunately, if inks are similar in property, then the same waveform can work well for both.

Optimizing Pulse Width

With this knowledge, it is common to begin the waveform optimization process by determining the proper pulse width for a given printhead and ink combination. In general, there is a near-quadratic relationship between pulse width and drop volume and velocity. The optimal pulse width is the one that will produce the highest drop volume and velocity, so finding that peak is what the first objective of the automated process will be.

In order to begin the process of finding the peak, we started with the default/recommended single pulse waveform for a given printhead. The pulse width used in this waveform would serve as a midpoint for our sweep. We set the automated script to adjust the pulse width from 50% below to 50% above that recommended setting. At each pulse width, the JetXpert system measured the drop volume and velocity at a consistent distance from the printhead. In addition, it captured an image of the drops.

For a Samba printhead, with a default pulse width of 2.18us, we swept through pulse widths from 1.1us to 3.3us in 0.1us increments. By capturing an image at each value (using double pulse) we are able to quickly judge the speed of the drop visually and can supplement with measurements if needed. Figure 3 below is generated using a combination of the JetXpert Add-Ons XSweep and Stitch.

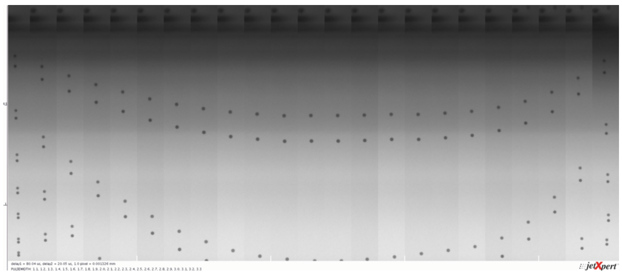

Figure 3. Varying pulse width from 1.1 to 3.3us

The top of the velocity curve is where the timing of the pulse gives the most efficient drop ejection for this combination of ink, head, and electronics. Based on our image, we can see that pulse widths of 2.1-2.2us seem to produce the highest drop velocity. We can tell because each slice of the image was taken at the same moment in time, and the drop has travelled furthest from the printhead in these slices. If you recall, 2.18us was our starting pulse width from the Dimatix Samba manual, and indeed it seems to be optimal based on this image.

This was a promising first step in our process for two reasons. First, the data generated from the sweep supports the underlying theory of the relationship between pulse width and drop volume and velocity. Second, and more importantly, we were able to automatically determine the same optimal pulse width as the printhead manufacturer.

Optimizing Voltage

Now that we know we’ve got the timing right, we can explore the connection between voltage and drop volume and velocity. Usually, there is a linear relationship between voltage and drop volume and velocity, up to a limit. The normal trade-off is that increased voltage also produces increased ligaments, so the objective is getting the highest possible velocity that produces a nice clean drop without a tail that breaks into satellites.

As we did before with pulse width, we tried a range of voltages and measured the drop velocity at each one. It is important to also keep an eye on the drop volume and satellite formation, as this will impact our decision. Our goal at this point was to determine the voltage setting that gives us our maximum volume and velocity without too many satellites. With our Samba printhead, we automatically swept through voltages of 21V-31V in 0.5V increments. The output is shown below.

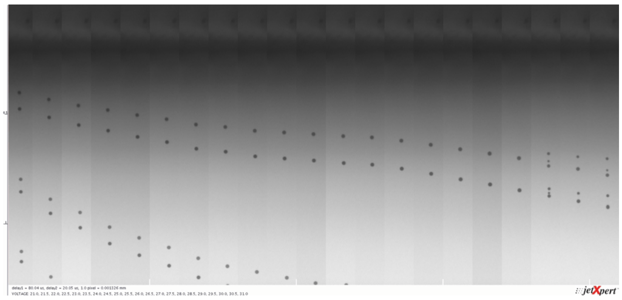

Figure 4. Varying voltage from 21V to 31V

Once again, the results seem to match the theory. The drop velocity increases linearly with voltage, up to a point where satellites are introduced. From here, we are able to make an educated decision about the optimal voltage for this waveform.

To recap, at this point we have created a single pulse waveform of optimal voltage and pulse width. These are the two fundamental parameters of the waveform, but we wanted to try to expand the capabilities of this procedure further. Next, we wanted to see if we could automatically test the waveform at different frequencies.

Exploring Resonance

It is common that a waveform that works well at one frequency might not work well at another. This all comes down to the timing of the pulses as the ink moves back and forth within the chamber. As the frequency of the printing is increased, the waves and movement created by a given pulse can start to interact with the previous one. At certain frequencies this is going to be reinforcing and the result is resonance.

The higher the printing frequency, the more likely that the pressure is not yet damped to zero when the next drop and pressure wave comes along, and thus the greater the potential for getting poor firing. If the ink is still moving, the previous pulse could either add to the pressure (higher velocity, more satellites, wetting) or detract from it (lower velocity). If your print speed is flexible, it is sensible to study the droplet formation at a range of frequencies in order to ensure your final print speed does not fall in a frequency range where resonance occurs.

To test this, we expanded our script to not only sweep through waveform design parameters, but the jetting frequency as well. The image below is our Samba waveform jetting at 1 – 30kHz in 1 kHz steps.

Figure 5. Varying frequency from 1 kHz to 30 kHz

We found that the drop formation from our optimized waveform looks pretty good across this range of frequencies. In a separate test with a Dimatix S Class printhead, we found that the optimized waveform did not always respond well at all frequencies.

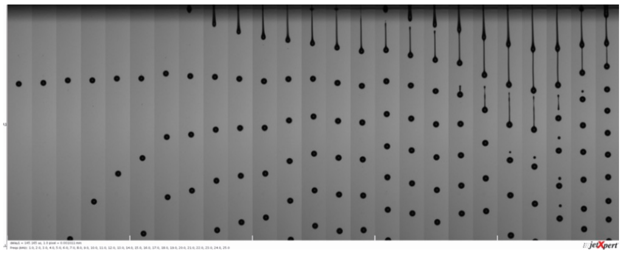

Figure 6. Example of frequency sweep with resonance

We noticed the jetting is a consistent velocity up until about 19 kHz, then the velocity spiked. In addition to the increased velocity, we also saw increased ligament length and satellite formation. This is resonance at work. At 19 – 24 kHz, the timing between the waveform pulses is such that the pulse is amplified by lingering momentum in the nozzle from pulse before it. With this knowledge, you can modify the design of your system to either avoid that frequency or use a different waveform for that range.

Introducing Multi-Pulsing

Another desired feature of the automated process is the ability to create more than one pulse in the waveform to increase drop volume. When more than one pulse is used in the waveform to create drops then we call it multi-pulsing. This is not to be confused with grayscale; we are still only producing one drop size, we are just using multiple waveform pulses to do it. Multi-pulsing can be useful for increasing the volume of the jetted drops if a single pulse is not capable of ejecting enough ink.

If we are going to use multiple pulses to create larger drops, we must begin by understanding the underlying timing of the ink moving in the head. In theory, we could do this by creating two identical pulses and looking to see what happens to the ejection as function of the gap between them. When the timing is right, the momentum of the ink in the nozzle will be increased by the second pulse, and we will see a faster drop once it is jetted.

Our process began with duplicating the optimized pulse that we created from before and adjusting the spacing between these two pulses, analyzing the jetting at each step. As before, we varied the spacing from the minimum allowable value to double the pulse width of each pulse. The best measurement to do is to look at the velocity of the second drop that comes out (if it does at all) since the speed of that drop is very sensitive to pressure fluctuation caused by the first pulse. At low pulse gaps in some head/ink combinations, the drops are likely to have merged before you get the chance to measure them, whilst in others the second ejection might appear as a bulge travelling up the ligament of the first. What is important is to find at what spacing the drop(s) you can measure go fastest. The peaks in the behavior are where the head resonance lies. Most successful greyscale waveforms work on or near the resonance period so that the ejection is optimized for a given amount of input.

When we duplicated our optimized Samba pulse and swept the pulse spacing from 1.4us to 3.2us in 0.1us steps, we produced the following image. It is pretty clear where the speed of the second drop is the highest, which is our resonant period.

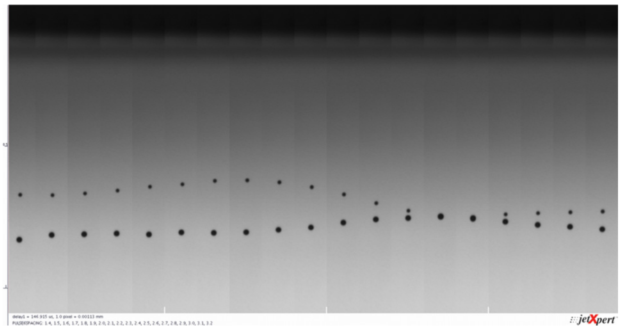
Figure 7. Varying pulse spacing from 1.4us to 3.2us

Now that we know our resonant period we can build a waveform that uses it.

Conclusions

The hypothesized procedure for optimizing the waveform was as follows: optimize pulse width, then voltage, and finally add additional pulses if needed and optimize spacing. Along the way, we would check the jetting at a range of frequencies to determine if resonance occurred. What we found was that each step of this procedure could be accomplished through automation.

For this testing, images and data were collected automatically, but the optimized value was determined by the user. An opportunity for further exploration could be to determine if the optimal value could also be selected automatically by the system. Because the system can identify drop volume and velocity automatically, it could in theory determine the waveform settings that produced the maximum values and then proceed to the next step in the waveform optimization. The challenge to overcome is locating the drops on the screen, because as the waveform changes, the position of the drops will also change if they appear at all.

Author Biography

Kyle Pucci received his degrees in Mechanical Engineering, Entrepreneurship, and Communication from Villanova University (2014) in Philadelphia, PA, USA. Since then, he has worked as Manager of Applications Engineering at ImageXpert Inc. His work has focused on developing new solutions for inkjet research and development and educating the market on inkjet analysis practices.