Scaling of Piezoelectric Drop-on-Demand Jets for High Resolution Applications

Marlene McDonald
Spectra, Inc., Hanover, New Hampshire

Abstract

As drop-on-demand ink jet systems strive for higher image quality, it is desirable to print with increased resolution. Higher resolution necessitates scaling jet designs to decrease drop volumes, while maintaining the high drop velocities needed for accurate drop placement. Using computer modeling in combination with experimental builds in machined carbon printheads, many variations of ink jet can be designed and tested in a short time. Finite element, lumped parameter, and three dimensional fluid modeling software are used to study mechanical properties, frequency response, and drop formation of Spectra's drop-on-demand ink jets. These tools allow the designer to develop a test matrix which is sensitive to the important parameters. In-house machining of printhead parts facilitates the building and testing of many jet designs in a single printhead. Using these tools in combination, the redesign of piezo jets for reduced drop volume was successfully demonstrated.

Introduction

In the beginning, Spectra ink jets were developed through the analytical efforts of key scientific personnel. Much of the theory of ink jets was simplified to one dimensional circuit theory, with appropriate approximations for the geometry of the jetting chambers. Jet pressures, volumes and velocities were predicted for various jetting configurations. The next step was to develop an extensive test matrix of experimental builds. This process led to the successful development of ink jets for 300 dpi printheads. Later efforts built on these results to design jets for 600 dpi printheads.

Although a fundamental understanding of ink jet operation is critical to the development approach, new PC based tools allow more comprehensive analysis of our ink jets. The use of computational fluid dynamics and finite element solid modeling software allows the engineer to incorporate fluid, structure and electrical interaction in three dimensions. The addition of modular, machined carbon jet structures has enabled rapid experimental iterations. Each carbon part can contain multiple designs and the modularity allows parts to be swapped for more combinations. This ability has allowed for improved turn around time from design to test.

Analysis Tools

The Lumped Parameter Model

One of the most useful modeling tools we have found for the analysis of piezoelectric ink jets has been a lumped parameter model based on the simulation software Extend™. Using this program as a base, we have developed a number of custom blocks to include the effects of the piezoelectric deflection, unsteady fluid flow, ink properties, and surface effects at the orifice. With these basic building blocks, we can construct models of any reasonable dimension or configuration. Though this approach treats the jet as a one-dimensional structure, it provides insight to the sensitivity of the jet design to voltage, frequency, pulse width, and ink properties.

The Finite Element Model

Finite element modeling has been invaluable in developing an understanding of the electromechanical behavior of the jet. The ANSYS program incorporates full three-dimensional piezoelectric properties into the jet model. This allows the prediction of PZT deflections as a function of electrode patterning, material properties and jet geometry. These capabilities have led to improvements in jetting efficiency, developed pressures, and jet-to-jet crosstalk.

Computational Fluid Dynamics

In order to gather more information about flow patterns in the jet, the Flow3D® code was chosen for its expertise in modeling the free surface in the ink drop. CFD provides the detailed information that was lacking with the Extend lumped parameter model. Flow3D® provides three dimensional, time-dependent, free surface analysis capabilities, enabling us to optimize jet trajectories, drop formation, and tail breakoff in our jet designs.

Modular Carbon Printhead Structures

A recent enhancement to Spectra's technology has been the use of sintered carbon as the structural element for printhead designs. First generation printheads were built with etched metal laminates, making design changes a long and expensive process. With conventional CNC machining processes, carbon printhead parts are fabricated repeatably and inexpensively. Experimental jet designs can be incorporated into printheads with very few constraints. For example, neighboring jets can be constructed with different pumping chamber lengths, widths, and depths. A matrix of experimental designs can be tested in a single printhead. The design can be revised, parts machined, and printheads tested in a very short period of time. This rapid test cycle has been very useful for product development.

An additional advantage of the carbon jet structure is the modularity of its design. In previous Spectra designs, the piezo-transducer was co-planar with the nozzle plate. In the new carbon designs, the jets have been repackaged to produce higher nozzle density. The piezo-transducer is oriented orthogonally to the nozzle, creating an edge shooter design. Thus the nozzle packing density is no longer limited by the transducer area. The jets are accurately located by the precision of the nozzle plate, and the edge shooter is connected to the nozzle plate by a set of small screws. This feature allows the piezo and orifices to be separated at this junction. This is a handy feature in terms of improving printhead yield. It is also a great feature when designing a test matrix. Transducer elements and orifices can be swapped back and forth to increase the experimental range without extensive printhead builds.

Design Approach

A recent effort to design jets for 15 picoliter operation utilized these modeling tools to define a study of the important jet dimensions, which were then built into carbon printhead parts. The lumped parameter model allows the designer to specify jet geometry, ink properties and material selection. Drive voltage, pulse width and jetting frequency are also input into the model. The code then predicts the drop volume and velocity, as well as detailed pressure information throughout the jet passages. We also used solid modeling to optimize the electrode pattern on the piezotransducer and computational fluid dynamics to model the effect of baffles and frequency response in the jet.

In this example, the 100 pL modular carbon jet design was taken as a starting point for the jet geometry. We then used the lumped parameter code to model the effect of changing four basic jet dimensions: pumping chamber length, pumping chamber width, orifice length and orifice diameter. The code predicted what range of variation would target the desired volumes and velocities. Spectra has considerable experience with a 30 pL jet design, which provided an intermediate data point for the analysis.

The following plots show typical output from the Extend^{TM} model for a 15 pL drop ejection. Figure 1 shows the input pulse to the PZT driver. Figure 2 shows the pressure response in the pumping chamber. As the pressure reflections are damped over time, it is possible to stimulate the jet without interference of the previous pulse. Figure 2 suggests that these jets can operate at a frequency of 20-25 kHz. Experience shows that they run successfully at still higher frequencies. Figure 3 shows the location, in picoliters of the ink meniscus. Negative volumes signify that the ink is retracted, as in the fill-before-fire mode. Positive meniscus position combined with positive chamber pressure creates the condition for drop ejection, as shown around 20 microseconds, when the 15 picoliter drop is ejected.

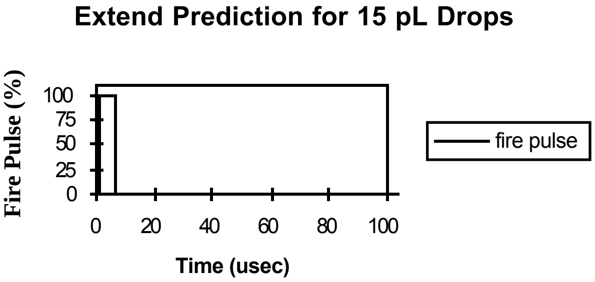

Figure 1. Applied Drive Pulse

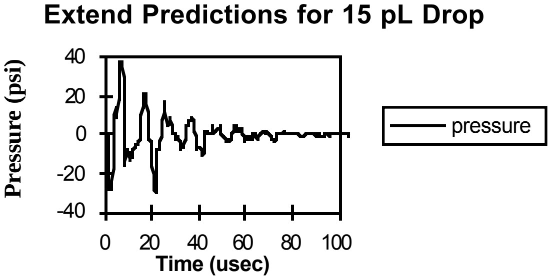

Figure 2. Pumping Chamber Pressure

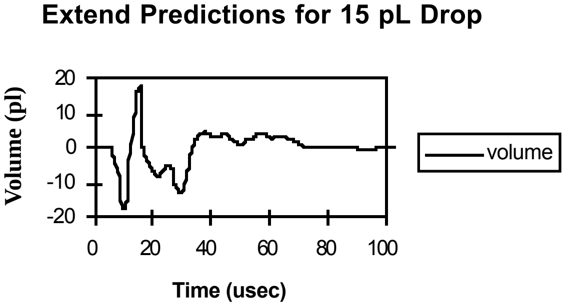

Figure 3. Meniscus Position

The next step was to design an experimental matrix to test the sensitivity of the jet design to these changes. Carbon parts were machined and multiple jet designs were built into each 128 jet printhead. For example, one printhead would combine both pumping chamber and orifice variations, rather than building each design into a separate printhead. Modular arrays were then swapped to increase the test matrix. Table 1 indicates the nature of jet variations within a printhead.

Table 1. Sample Test Configuration

Jet Design	PC Length	PC Width	OP Thickness	OP Diameter
A	a	a	a	a
B	a	a	a	b
C	a	b	a	a
D	a	b	a	b

Experimental Results

The matrix of jet designs was then tested in the laboratory to determine the success or failure of the analysis. The experimental setup consists of drive electronics, three-dimensional motion system, synchronized LED strobe, and a video system. This allows us to observe the drop formation, jet stability and to measure velocity and volume of the drops. All of the variations were tested for volume, velocity, frequency, voltage and pulse width response. The 15 pL target volume was easily achievable, as well as a range of volumes in that vicinity.

The criterion for choosing a jet design was to produce 15 pL drops at a velocity of 8 m/s over a range of frequencies. It was necessary to provide enough design latitude that we could expect reasonable production yields. Figure 4 shows the velocity plot for one of the test heads at constant voltage. This printhead combines two pumping chamber widths and two orifice diameters for a total of four jet variations (as shown in Table 1). We see that increasing the pumping chamber width by 15% (A to C, or B to D) creates an increase in velocity of about 30%. We also observe that decreasing the orifice diameter by 15% (A to B, or C to D) creates a velocity increase of 25%.

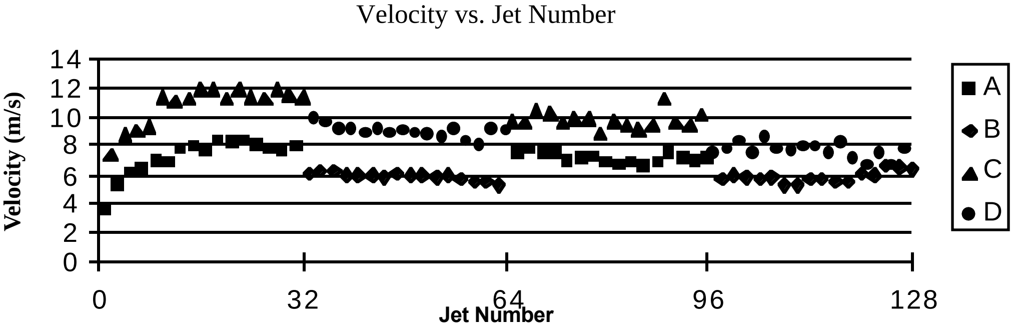

Figure 4. Velocity vs. jet number for test printhead. Showing four jet variations and their effects of velocity

The volume of each jet design was then measured at constant velocity over a range of pulse widths, to give an understanding of what volumes could be expected at normal operating conditions. Figure 5 shows the drop volumes for the jet geometries described above. Designs B and D, having larger orifices were shown to throw excessively large drops. Designs A and C fell right in the target window for drop volume. Combining information from Figures 4 and 5, we can determine the optimal jet geometry. The pumping chamber in design C is 15% wider than design A, allowing more PZT deflection per volt applied. These jets threw faster drops than design A, without a large increase in volume. For this reason, the orifice diameter and pumping chamber widths from design C were chosen for the 15 pL jet design.

Figures 6 and 7 compare the Extend predictions for drop volume with the experimental results. In Figure 6, the model demonstrates excellent correlation with the effect of changing the orifice diameter. However, the volume is over- predicted by about 20%, due to discrepancies related to the pumping chamber length predictions. In Figure 7, the model predicts that a 20% decrease in pumping chamber length will reduce drop volume by about 10%. The experiment demonstrates that the volume was more sensitive to pumping chamber length than predicted.

As a result of the modeling and experimental builds, we identified several jet designs which would satisfy our performance needs. Based on manufacturability, efficiency and performance, we were able to determine which design would best suit our needs. Using the sensitivity results from the test matrix, we were able to tweak the design when fine tuning was needed to satisfy the customer's requirements. We have also increased our knowledge about jet perfor-

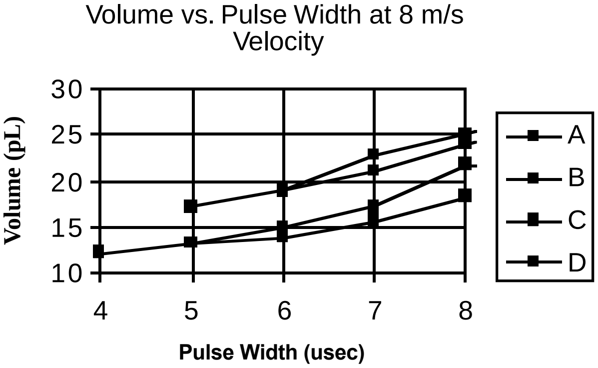

Figure 5. Volume vs. pulse width for test printhead. Showing four jet variations and their effect on volume

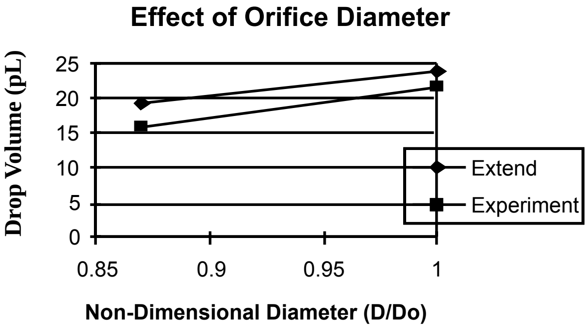

Figure 6. Comparison of Extend predictions with experimental results for sensitivity to orifice diameter

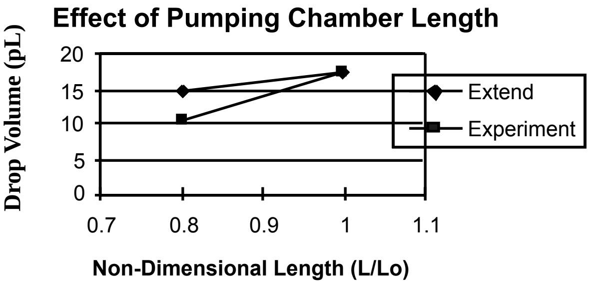

Figure 7. Comparison of Extend predictions with experimental results for effects of pumping chamber length.

mance and have new tools to implement for the next design challenge.

Conclusion

A new jet design, which throws small enough drops for very high resolution printing, was developed in a short period of time by using a combination of computer modeling and experimental tools. These same tools are essential in sustaining development of a jet design through to a finished product, as well as helping to create the next new design for future printhead development.

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