Ink Jet Modeling For Development of New High Performance Ink Jet

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Abstract

Piezoelectric, drop-on-demand ink jets typically require a long development cycle and numerous redesigns to meet design goals. Numerical modeling of the ink jet can be used to speed this process and improve the overall result of the development effort. By using a combination of modeling tools such as finite-element structural and fluid modeling and a proprietary lumped-parameter model of the ink jet, ink jet performance can be estimated without the need to fabricate and test. This can save significant develop time and effort. Investigations of ink jet dimensions such as PZT thickness, pumping chamber, nozzle and other dimensions, and their effect on performance characteristics such as drop mass and velocity, input voltage and frequency response help guide the design of prototype ink jets. Sensitivities to fabrication tolerances can be minimized by determining performance optimums and selecting design points with low sensitivities to known tolerances. Spectra Inc. has applied these tools to the development of high frequency, high performance ink jet designs. Ink jet performance data and comparison to model predictions help improve the modeling tools.

Introduction

Performance of a piezo driven, drop-on-demand ink jet device is governed by a complex array of physics including fluid dynamics, wave propagation, electronics, solid mechanics, surface energy, ink properties, etc. All of these interact in some way to produce the overall behavior of the ink jet. Some of the most important performance parameters are drop velocity, drop mass, required voltage and frequency response. If the performance of an ink jet can be accurately modelled and predicted, then substantial development effort can be saved when developing new products, and current products can be improved.

Numerical modeling of ink jets at Spectra uses at least three separate approaches. The CFD package, Flow3D^R, is a valuable tool for predicting drop formation, jet straightness and details of the flow passages. A complete model of an ink jet from the reservoir to the drop flight has also been developed using Flow3D^R. However, this model has some limitations. Run times on a modern workstation are fairly long when using a high resolution grid. Modeling fluid/structure interactions, such as wall compliance in the pumping chamber, with Flow3D^R is complex. These interactions can be critical to the overall performance of the jet. ANSYS^R is a useful tool for modeling the structure and can model the fluid/structure interaction. ANSYS^R therefore can be used to predict PZT behavior, pressure development in the pumping chamber and the effects of structural compliance on wave propagation and flows. ANSYS^R, at the time of this writing, can model drop formation (free surface) in two dimensions only. A full ANSYS^R model of the ink jet, including fluid/structure interactions, has been built and is impractically large. It is likely that any finite element or finite difference model of an entire piezo driven drop-on-demand ink jet will be quite large. To address the shortcomings of the available modeling packages, Spectra has developed it's own modeling tool for predicting ink jet performance. Spectra's model uses the Extend^R simulation package and is programmed in a language called "ModL". Spectra's model is a modular, one-dimensional lumped parameter model that treats an entire individual jet from the reservoir to the fired drop.

Ink Jet Model Features

The ink jet model includes effects for flow development time in the ink jet flow passages and nozzle, for compliance in the ink jet structure, PZT compliance and fluidic compliance, fluidic inductance, PZT actuation, filter resistance, and drop formation. The pumping chamber and flow passages are modelled as an equivalent L, R, C circuit, with element properties calculated based on geometry, structural properties and fluid properties.

The model is modular, consisting of building blocks that can be assembled in various configurations to represent different configurations of an ink jet. Figure 1 shows a sketch of one possible model configuration. The blocks labeled "FILL", "DUCT", "TURN", "PUMPING CHAMBER" AND "DESCENDER" are based on the same basic model building blocks with different geometries used to represent different parts of the jet. All blocks use custom code developed at Spectra.

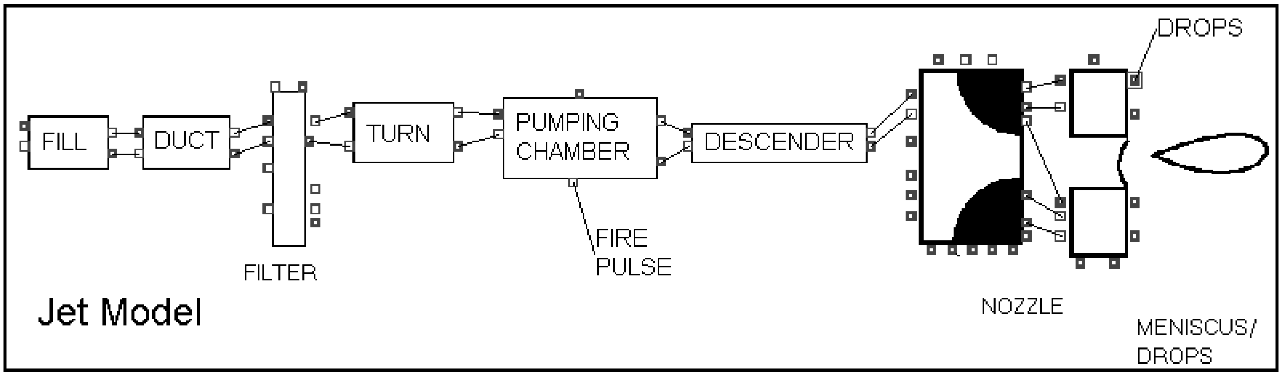

Figure 1. Sketch of Extend^R Modular Jet Model

Each Block consists of one or more internal elements. The internal elements connect in series, more or less creating a one dimensional finite difference structure. The Extend^R program performs the time integration. Figure 2 shows that the pumping chamber block contains ten internal elements.

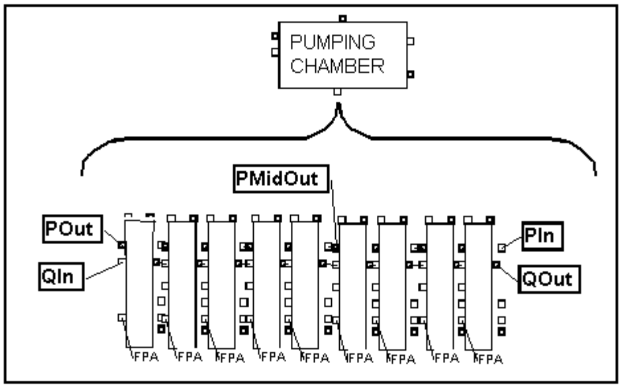

Figure 2. Sketch of Pumping Chamber Block

The individual elements of the model contain the system equations for the L, R, C, lumped parameter representation of the fluid duct. Pumping chamber elements include a source term for the PZT; all elements include compliance terms for the structure and fluid. Figure 3 shows a sketch of the L, R, C model in the duct element.

Fluidic inductance and resistance vary with time. As fluid begins to flow in a duct, the flow resistance is high because the flow profile has not yet developed and the shear rates at the wall are much greater than for fully developed flow (proportionately to the centerline flow velocity). Figure 4 shows the resistance variation vs. non-dimensional time. The non-dimensional time (Tstar) is defined by Equation 1. Both Flow3D^R and analytic results are given.

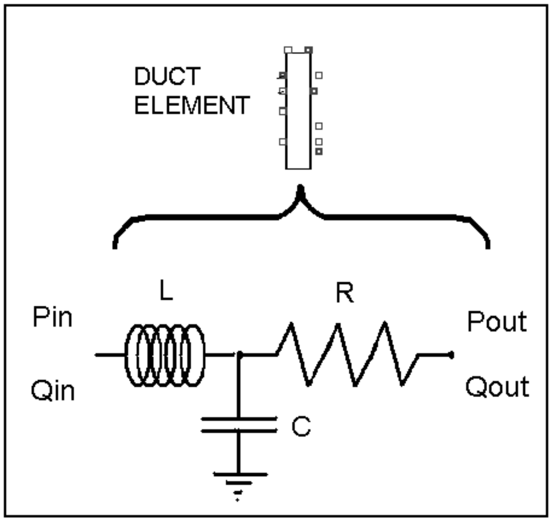

Figure 3. Sketch of Duct Element Model

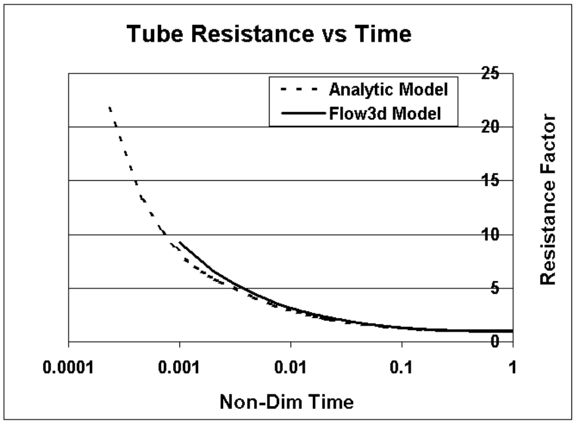

Figure 4. Tube Resistance vs. Time

$$Tstar = Time * nu / r^2 \quad (1)$$

where: nu = kinematic viscosity
r = tube hydraulic radius

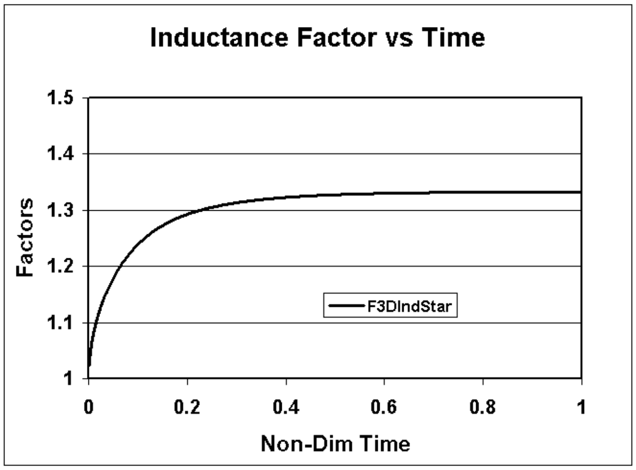

Figure 5. Tube Fluidic Inductance vs. Time

Figure 5 shows the variation in non-dimensional inductance with time. These values were derived from a Flow3D^R model of a duct. Initially, the fluid in the tube moves as a slug. As the flow develops, the core moves faster and the total energy is higher than that for slug flow of the same volumetric flow rate. These flow development relations for resistance and inductance apply to laminar flow. Typically, Reynolds numbers in an ink jet are less than 100 so the laminar flow approximation is appropriate.

The nozzle resistance can be modelled with a term for the dynamic head losses due to acceleration of the fluid. Since velocity in the nozzle exit is typically high, the dynamic head term is important. So, nozzle resistance varies with time and velocity. Figure 6 shows the variation in nozzle resistance vs. time, for a 50 micron nozzle. This figure is based on Flow3D^R model runs.

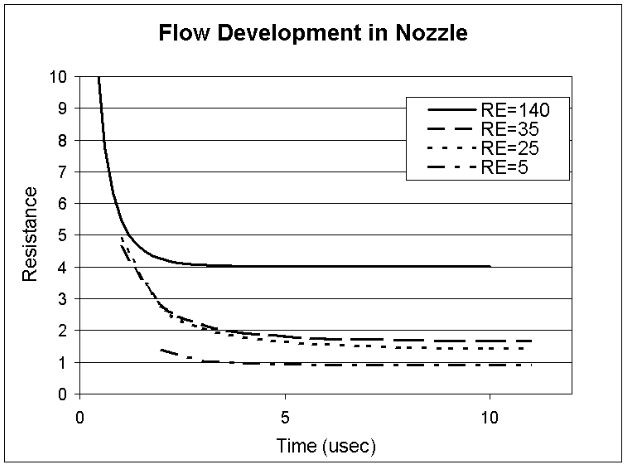

Figure 6. Flow Development in Nozzle

Finite Element and Finite Difference Models

The ink jet model requires several inputs to enable it to accurately represent the performance of a particular jet. These include fluid properties (viscosity, density, bulk modulus and surface tension). PZT displacement vs. voltage is required. PZT displacement can be measured with a tool such as the Laser vibrometer or an interferometer, but this requires that a jet or similar structure with the PZT already be built. Spectra has used the finite element modeling code ANSYS^R to model PZT displacement and structural compliance in the pumping chamber. Exact geometry of every flow passage in the jet, including a detailed nozzle profile, is required. Flow passages with convoluted/complex geometry can be modeled in ANSYS^R or Flow3D^R.

ANSYS^R is used to calculate performance of the PZT. The pumping pressure, PZT compliance and PZT displacement are estimated through the finite element model. Figure 7 gives a non-dimensional plot of the pressure in the pumping chamber vs. component thickness, for several PZT configurations. Figure 7 shows that by varying the thickness, the pressure developed in the pumping chamber can be maximized. Stress in the material and other considerations are also important.

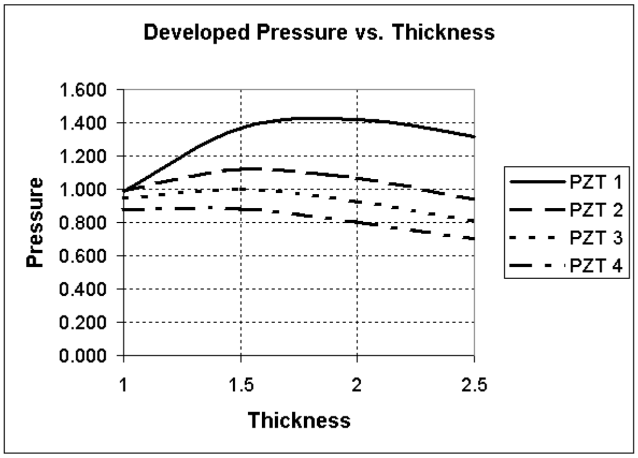

Figure 7. Pressure in Pumping Chamber vs. PZT thickness

The results of the ANSYS^R model, combined with the ink jet model, give an estimate of voltage required to fire a drop at the design velocity and mass. By using the PZT properties of compliance and displacement calculated in the finite element model, the Extend ink jet model will estimate the performance of the jet with different PZT configurations. Figure 8 shows the voltage to fire a drop divided by the design voltage vs. non-dimensional PZT thickness for various pumping chamber configurations. For these cases, the plot suggests that a thin PZT is desirable. Other considerations will limit how thin the PZT can be.

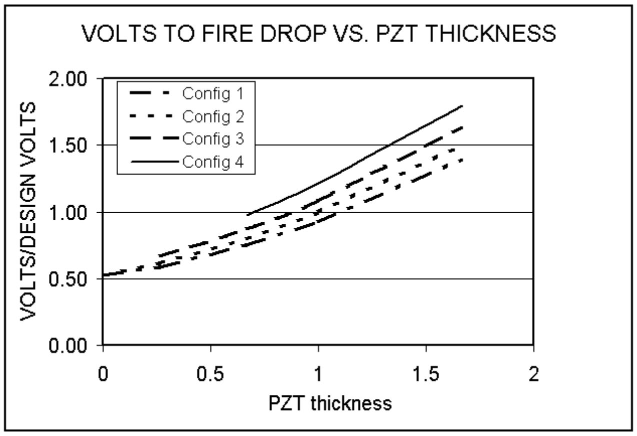

Figure 8. Volts to Fire Drop vs. PZT Thickness

New Jet Development

The modeling tools described above have been used in the development of new printhead designs at Spectra to create designs with smaller drops (for some designs), larger drops (for some designs), higher resolution, higher frequency operation, less expensive manufacturing, improved frequency response improved packaging, etc. A range of jet designs had to be built based on the design used in the jet model. Testing was required to assure that all operating requirements have been met.

Conclusion

Modeling tools when properly applied can assist in the understanding and improvement of existing products, and the design of new products. No single modeling tool is sufficient for analyzing the performance of an entire ink jet. The combination of off-the-shelf finite difference and finite element modeling tools with Spectra's ink jet model enables the estimation of jet performance for a wide range of jet designs. These predictions can be used for the development and improvement of ink jets. The number of jets that must be tested can be reduced.

References

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Biography

Robert Hasenbein received his ME in Mechanical Engineering from the Thayer School of Engineering at Dartmouth College. His work at Spectra has focused on improvements to the ink jet modeling tools, CFD modeling and new ink jet development.