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MULTI-DISCIPLINARY SIMULATION OF PIEZOELECTRIC DRIVEN MICROFLUIDIC INKJET

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ABSTRACT

Piezoelectric inkjet technology is critical to documentation, graphic arts and manufacturing applications. Physical modeling plays an essential role in the development of this technology. In this paper, we present a comprehensive, multi-level, inter-disciplinary simulation approach for piezoelectric inkjet design. This includes a high-fidelity, inter-disciplinary detailed simulation method for architecture investigation, and a much faster reduced-order modeling approach that enables interactive design of voltage waveforms. Simulation results are compared with experimental data. The multi-level inter-disciplinary simulation methodology presented here can be applied to designing MEMS and microfluidic devices and systems [1].

1 INTRODUCTION

Despite the movement toward a “paperless” world for the last 30 years, there is still a growing demand for simple, low-cost, high quality inkjet printers. Inkjet is one of the handful MEMS “success stories” with over 100M inkjet chips produced every year [2]. Today, inkjet printing, as one of the major digital printing enablers, is expanding into a much larger commercial printing arena, displacing the conventional analog offset press with an annual growth rate of 8%.

Besides the documentation and graphic arts applications, inkjet printing also plays a key role in the development of manufacturing technologies. The demands for automation, miniaturization, cost reduction and environmental concerns have made inkjet an attractive technology for the distribution and patterning of materials for a wide variety of applications including flat panel displays, liquid crystal displays, polymer light emitting diodes, flexible displays,[3] printed circuit boards, RFID tags, wearable electronics,[4] and rapid prototyping [5]. In addition, inkjet's ability to meter pico-liter to micro-liter amounts of liquid samples with rapid speed and high precision makes it one of the principal microfluidic liquid handling methods for life science applications including DNA research, drug dosing, and analytics [6].

Compared to other leading inkjet technologies, piezoelectric inkjet has fundamental advantages in its ability to jet a wide variety of liquids and to deposit them onto a diverse set of substrates with well-defined patterns. This is particularly significant in light of the applications in graphic arts, printed electronics and life science where the jetting liquids often times are not aqueous and have a wide range of physico-chemical properties.

Piezoelectric inkjet design is primarily driven by the demand for enhanced packing density and jetting performance. The jetting performance is characterized by drop volume and firing frequency. The drop volume determines the print resolution; drop volume and firing frequency together determine the liquid flux. In addition, jetting velocity affects properties that determine the quality of the jetting such as the jet straightness, and the generation of satellites. Both drop volume and drop velocity display variation over firing frequencies. It is desired to keep such variation within about 10% for acceptable print quality.

Numerical simulation has become an integral component of our piezoelectric inkjet design practice. It has been used to investigate the device physics, to uncover the physical insights that are otherwise difficult to measure in experiments, and to narrow the optimal design space that meets the desired drop volume, firing frequency and print quality. Numerical

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simulation has also been used to optimize experimental strategies and to interpret experimental results.

In this paper, we present our inter-disciplinary simulation methods and solutions for piezoelectric driven inkjets. Section 2 provides a brief description of piezoelectric driven inkjet and its operating methods. Section 3 presents our inter-disciplinary numerical simulation methods and results. Section 4 discusses the resonating fluid dynamics and the development of a reduced-order model. We conclude in Section 5.

2 DEVICE DESCRIPTION AND OPERATING METHODS

Fig. 1 shows a schematic view of a piezoelectric inkjet. It consists of a piezoelectric actuator that is mounted at one side of a microfluidic channel. One end of the microfluidic channel connects with a common liquid reservoir and the other end narrows down to form a nozzle. Initially, surface tension draws the liquid from the reservoir and fills the microfluidic channel. A slight negative pressure is applied in the reservoir to pin the liquid free surface at the nozzle opening that prevents liquid from dripping out. To fire a droplet, a carefully designed voltage waveform is applied to the piezoelectric actuator. The resulting actuator deformation first enlarges the microfluidic channel such that a negative pressure is generated in the channel. The pressure propagates towards both ends of the microfluidic channel and is reflected at the reservoir, which acts as an open end (constant pressure), and at the nozzle, which acts as a closed end (zero normal velocity). The reflected pressures travel toward the channel center just in time for the actuator to contract. The timing of the contraction is designed so that the resulting positive pressure resonates with the reflected pressures. As a result, the liquid movement toward the nozzle acquires sufficient momentum to overcome the surface tension and a liquid jet is ejected from the nozzle. The velocity disparity along the jet works in concert with the surface tension to break the jet into a discrete droplet. Inside the microfluidic channel, the liquid is drawn from the reservoir to replenish the liquid mass lost due to jetting, and the liquid movement is dampened due to viscous shear.

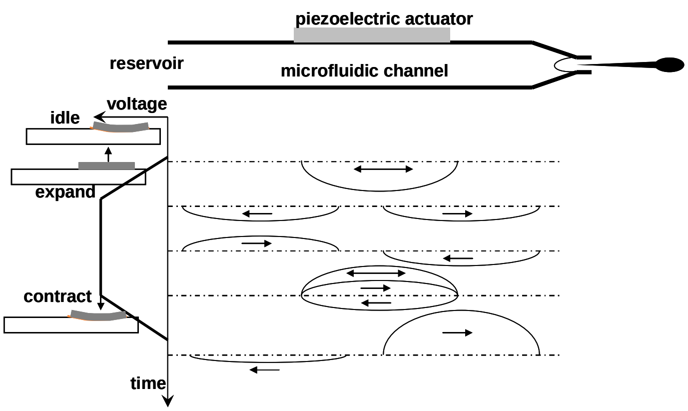


Figure 1. Piezoelectric inkjet and its working principle.

Ideally, the next firing waveform arrives only after the liquid kinetic energy in the microfluidic channel is dampened to zero. In practice, to maximize the firing frequency and, thus, the liquid flux, the second firing signal arrives as soon as the liquid kinetic energy is greatly reduced to an acceptable level. Consequently, there is a cycle to cycle interaction which appears as a variation in drop volume and drop velocity over firing frequencies.

The operation described above is referred to as "pull-push" or "fill-before-firing". This method provides higher drop volume due to the utilization of resonating fluid dynamics. In addition, the jet forms inside the nozzle and is not sensitive to the quality of the nozzle surface area, which is a major cause of unsatisfactory drop uniformity.

3 INTER-DISCIPLINARY SIMULATION METHODS AND SOLUTIONS

A complex array of physics is involved in the piezoelectric inkjet operation: coupled piezoelectric-mechanics transforms the electric energy into the piezoelectric induced strain; coupled fluid-structural interaction provides the structural movement to excite the liquid inside the microfluidic channel and the liquid pressure, in turn, affects the structural deformation; carefully engineered viscoacoustic flow harnesses liquid kinetic energy; free surface dynamics govern the jetting formation, drop release, and liquid replenishment within the microfluidic channel.

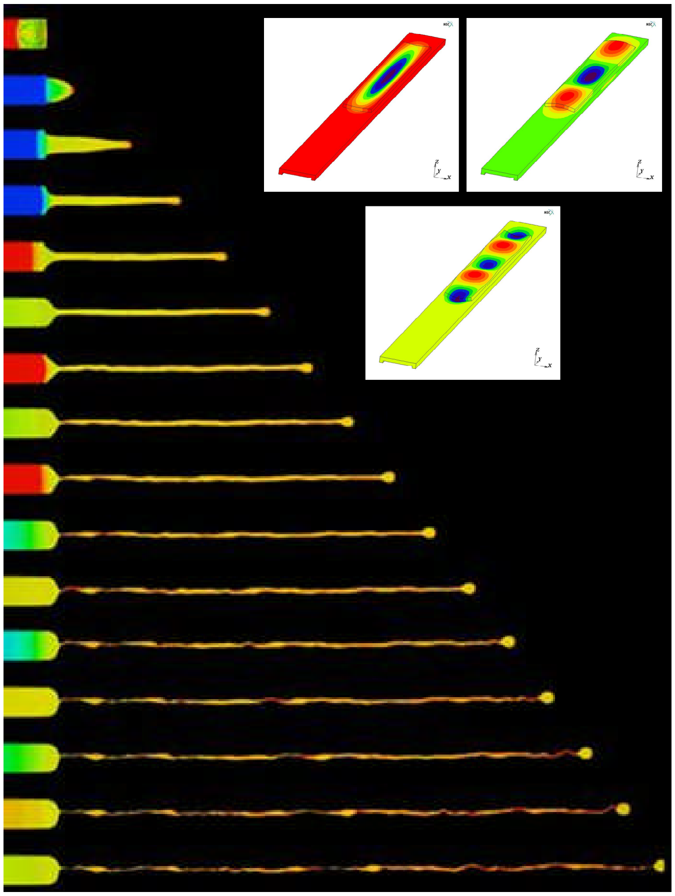


Figure 2. Inter-disciplinary simulation of piezoelectric inkjet formation. Time interval is 6% of firing cycle.

There is no off-the-shelf simulation solution yet that can provide a high fidelity, fully-coupled piezoelectric-structural-viscoacoustic-free surface dynamics simulation solution with reasonable computational time. We have developed our in-house simulation solution by integrating specialty commercial simulation packages and our custom codes. We selected Abaqus (SIMULIA, Providence, RI) to provide the piezoelectric-fluid-structural solution, and FLOW-3D (Flow Science, Inc., Santa Fe, NM) to provide viscoacoustic-free surface solution. A custom bridge code was developed that enables the Abaqus fluid-structure interaction solution, as a function of both space and time, to provide direct actuation input for FLOW-3D. The custom bridge code simulates both the compression and the shear waves generated by the actuator deformation and produces accurate flow rate estimation. In addition, we have adopted CoventorWare (Coventor, Cambridge, MA) to streamline and automate the geometry creation and exchange among different simulation packages.

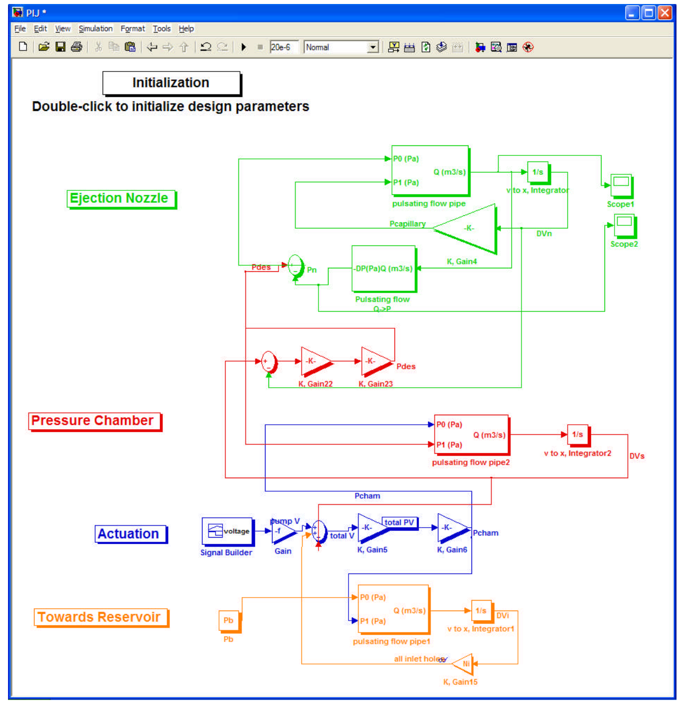
Our simulation has been validated with the experimental measurements. In addition, even for a complex design that consumes 18 million nodes, a full simulation solution can be delivered within 2~3 days, using a workstation with two Xeon (quad core) 3.0GHZ processors. Our simulation methods have been applied to several piezoelectric inkjet development programs and have achieved significant design cycle reduction. Fig. 2 shows an example simulation solution. This simulation is transient and three-dimensional. It shows jet formation during one firing cycle. Because a highly viscous liquid is used, a long, thin liquid filament occurs that connects the drop head and the meniscus at the nozzle opening until the occurrence of the Rayleigh breakup. Using the released drop velocity as the characteristic velocity, the capillary number is about 4. Fig. 2 also shows the mode shapes of the structural deformation. The structural vibration frequency is about 15 times higher than the Helmholtz frequency within the microfluidic channel.

The relatively low simulation turn-around times achieved with the above approach have enabled Design of Experiments approaches to be used. Simulations have been applied to sweep through the multi-dimensional design space and simultaneously evaluate the effects of material compositions, material properties, geometrical features, and geometrical dimensions. Sensitivity analyses have been performed to investigate manufacturability; optimal designs are identified based upon carefully selected performance metrics.

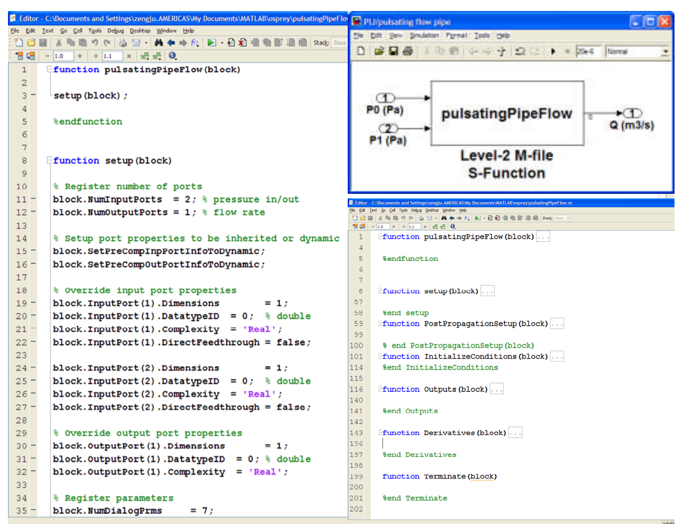
4 REDUCED-ORDER MODEL

Piezoelectric inkjet utilizes resonating fluid dynamics to produce desired jets. In addition to the geometrical design ("silicon-level design"), voltage waveform offers an additional design dimension. Voltage waveform characteristics is known to have critical impact on jet formation and is used to tune drop volume and drop velocity, reduce or eliminate jet tail, accelerate the dampening of the liquid flow, and vary drop volumes to achieve gray scale. In addition, by embedding sensors inside the inkjet, much higher jetting stability and accuracy can be achieved by feed-back loop control that dynamically adjusts the waveform according to the sensor readout.

Waveform design requires a different simulation capability. It demands much shorter simulation time, on the order of minutes, to enable interactive design. For this, it accepts approximate results that capture the first order effects. A reduced order model [1][7] was created as a simulation aid for waveform design. Liquid flow inside the microfluidic channel is calculated by a 1-D viscoacoustic model that assumes the through flow is dominant, the rate of local density change due to pressure change is constant (liquid acoustics), the flow component corresponding to the Helmholtz frequency has a high Womersley number, and the flow component corresponding to the surface tension induced capillary frequency has zero Womersley number (Poiseuille type flow) [8]. The flow rate exiting the nozzle end of the microfluidic channel is translated into drop volume and drop velocity by a phenomenological jetting model.



(a)



(b)

Figure 3. (a) System schematic of piezoelectric inkjet. (b) Implementation of 1-D viscoacoustic flow model. Left is the template (S-Function); top-right shows the model symbol; bottom-right shows the complete template with detailed implementation folded.

Fig. 3(a) shows a schematic of a piezoelectric inkjet including actuation, pressure chamber and ejection nozzle. It is implemented using Simulink (MathWorks, Natick, MA). Fig. 3(b) shows the implementation of 1-D viscoacoustic flow model, one of the key components of the piezoelectric inkjet system schematic responsible for capturing the resonating fluid dynamics. Fig. 3(a) illustrates a system schematic of a single printhead. One of the key advantages of this type of simulation is the ability to simulate a much larger systems, for instance, a die that includes many nozzles that may fire concurrently. Simulink's hierarchical abstraction capability can readily turn Fig. 3(a) into a sub-system model that encapsulates all the single printhead level's complexities, and can be used as a building block for schematic creation of much larger systems.

Fig. 4 illustrates the effect of voltage waveform on jetting. The jetting images at the top of Fig. 4 are experimental results obtained by a custom developed strobic microscope. Each image, corresponding to a different voltage waveform applied to the same piezoelectric inkjet, is taken at the same time in reference to the contraction. From left to right, the pulse width increases with a constant interval. Position of drop head indicates the variation of drop velocity as a function of the pulse width. The figure at the bottom shows the results from the reduced-order model are in good agreement with experiment.

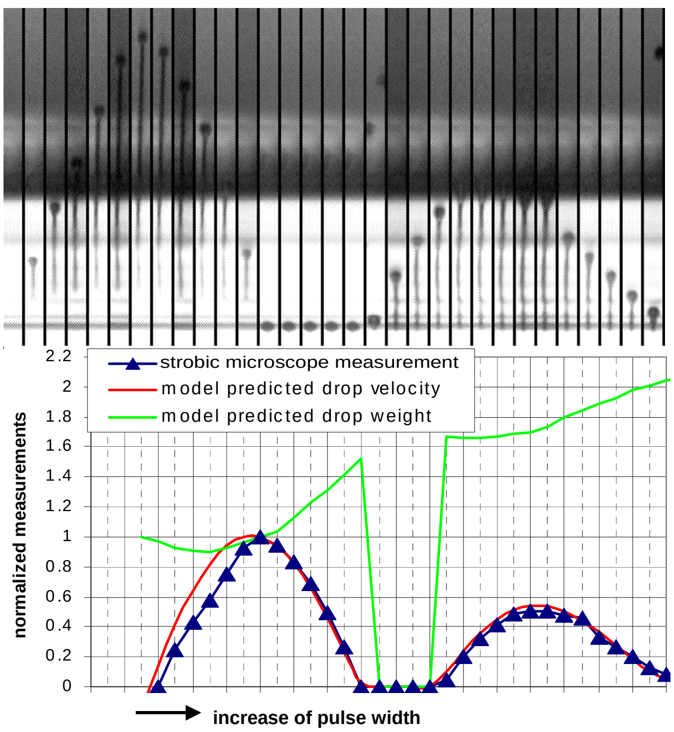


Figure 4. Experimental and modeling results on the effect of voltage waveform on jetting.

5 CONCLUDING REMARKS

We have presented multi-level, inter-disciplinary simulation solutions for piezoelectric inkjets. A high-fidelity, inter-disciplinary, detailed simulation approach was used that integrates specialty commercial simulation tools to achieve both high accuracy and acceptable computational time. This simulation method has been validated and has been found to be very useful to inkjet architecture design. We have also shown a much faster reduced order model that captures the first order effects. The reduced order modeling approach is particularly useful for voltage waveform design and has been found to be in good agreement with experimental data. The multi-level inter-disciplinary simulation methodology presented here can be applied to the design of a broad range of MEMS and microfluidic devices and systems [1].

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