Free surface flow and acousto-elastic interaction in piezo inkjet

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ABSTRACT

Modeling plays an essential role in our research on new inkjet technologies. Structural modeling with Ansys includes piezo-electricity. Acoustic modeling in Ansys and Matlab involves fluid-structure interaction. CFD modeling with Flow3D includes wall-flexibility and free surface flow with surface tension. Added to our measurements this reveals the phenomena involved in our main goal: firing droplets of ink at a very high rate with any desired shape, velocity, dimension and a reliability as high as possible.

Keywords: inkjet, acoustics, drop formation, two-phase flow, fluid-structure interaction

1 INTRODUCTION

Inkjet is an important technology in color document printing. Océ applies inkjet in its wide format color printing systems, Figure 1.

Figure 1: A recently introduced wide format inkjet printer, the Océ TCS400.

New piezo technologies provide opportunities towards higher productivity, quality and reliability.

2 PRINTHEAD BASICS

A long ink channel with a nozzle is the basic geometry of the inkjet device, Figure 2. A piezo actuator element drives each channel. To fire a droplet, an electric voltage is applied deforming the structure resulting in pressure waves inside the channel. The pressure waves propagate in both directions and will be reflected at changes in cross-section and compliancy of the channel structure. The channel structure is designed to get an large incoming positive pressure wave at the nozzle. In the small cross-section of the nozzle acceleration of the ink movement results in drop formation.

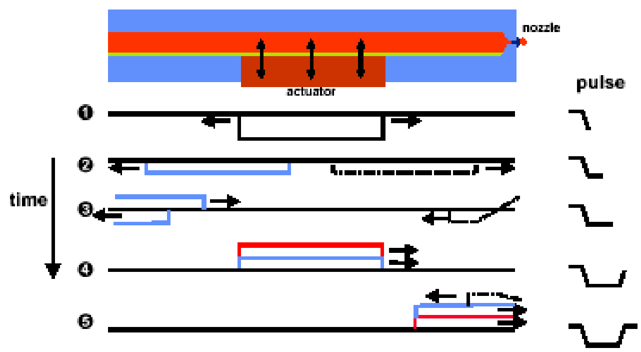

Figure 2: Actuation taking into account channel acoustics.

3 MEASURING

Droplets are measured by means of various optical methods like stroboscopic illumination at drop formation rate and high-speed camera recordings with a Phantom V7 camera. With laser-Doppler measurements meniscus movements without drop formation are recorded. These measurements give details on ink flow outside the printhead. The phenomena inside the channels are difficult to measure. The only suitable method uses the actuator also as a sensor. Switching the piezo elements from the electronic driving circuit to a measuring circuit gives a recording of the average pressure inside the ink channel.

4 MODELING

We need more information on the phenomena preceeding the drop formation for a better understanding of the physical processes. Details on ink flow and acoustic pressure waves are only available through modeling.

Two main aspects in modeling piezo inkjet are the acousto-elastic interaction and free surface flow. To model printhead dynamics and the interaction with ink acoustics the FEM code Ansys is used. Matlab is used for acoustic calculations based on the "narrow gap" theory. For free surface flow with surface tension (drop formation) and its impact on channel acoustics we use the VOF code Flow3D.

4.1 Structural modeling

When a voltage is applied to one piezo element also the neighbouring channels will be deformed. This results in a direct cross-talk effect. Secondly the generated pressure waves will deform the structure too and this results in an induced cross-talk effect. Bridge structures with balanced elongational and bending deformation components are designed using Ansys simulations and eliminate these cross-talk effects. To take into account structural details like glue layers, a static full structural analysis in a 2D plain strain model is used with standard structural and piezo-electric elements. Figure 3 shows the deformation of the piezo finger structure below a channel block in a semi cross channel configuration.

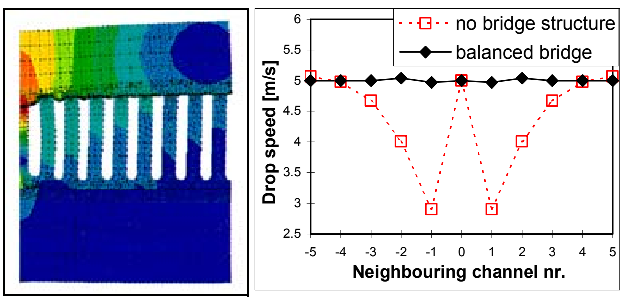

Figure 3: Calculated deformation of the printhead structure and measured resulting cross-talk effect on drop speed.

On actuating more piezo elements a range of vibrational modes of the printhead structure is excited. Modal analysis with 3D Ansys models of the complete printhead structure helps us to identify the individual modes of these printhead dynamics.

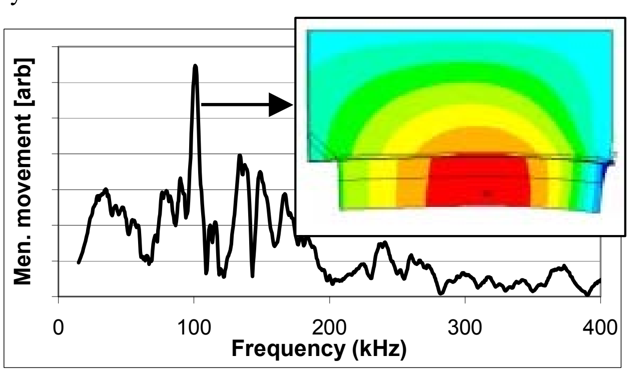

Figure 4: Measured meniscus movement and calculated shape and strain of the dominating mode.

In Figure 4 the frequency characteristic of the meniscus movement from a sinusoïdal small signal actuation of 128 piezo elements on the other side of the printhead is shown as measured with our laser-Doppler equipment. For the dominating frequency the shape of the corresponding mode from modal analysis is shown in a cross-section along the channels. The piezo actuator is located at the bottom and the nozzles are located at the left hand side.

A special application is the simulation of impedance spectroscopy spectra of the piezo elements [1]. Ansys simulations identify the relevant modes. Mathematical modeling give the effective macroscopic material parameters derived from the true micoscopic material properties and for example a multilayer structure. We developed these mathematical models in Matlab based on coupling the Maxwell equations for the electro-quasi-static case and linear elasticity for the specific modes.

4.2 Acoustic modeling

We implemented a mathematical model in Matlab based on the “narrow gap” theory [2]. A very important effect of the flexible channel structure is the decrease of the effective speed of sound. Only a quasi-static compliance of the channel cross-section is taken into account and this results in a typical effective speed of sound inside the channels of 800 m/s instead of 1200 m/s.

For efficiency, the actuation pulse has to be tuned to the main frequency characteristics of the meniscus movement. The amplitude of the meniscus movement resulting from a small sinusoïdal actuation as a function of the frequency is shown in Figure 5.

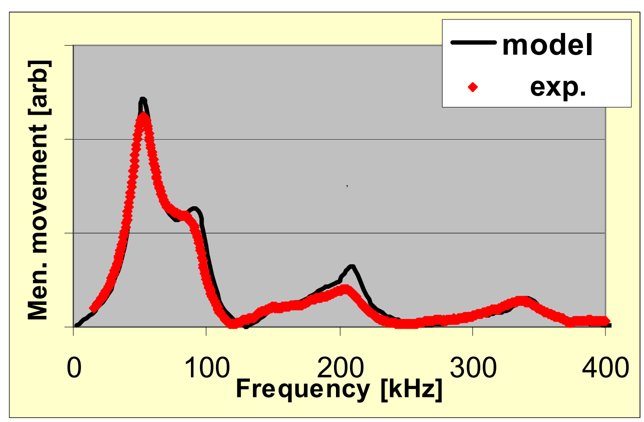

Figure 5: Frequency characteristics of meniscus movement as calculated and measured with laser-Doppler.

Complex interactions of printhead structure dynamics with channel acoustics are identified by acoustic modeling with Ansys. The 3D structural models are extended with FLUID80 elements for the ink domain, connected by constraint equations. The mesh structure of the ink domain is adapted to the velocity profile as predicted by the shear wave number [2] to reduce the number of elements. An example is given in Figure 6. Maximum acoustic coupling is reached on matching frequencies and deformation shapes. Identifying the most disturbing modes is a first step in suppressing unwanted cross-talk effects. The most complete version of this model also includes the entire ink reservoir. From this complete model design specifications for the reservoir can be derived to avoid acoustic cross-talk effects through the ink domain in the reservoir.

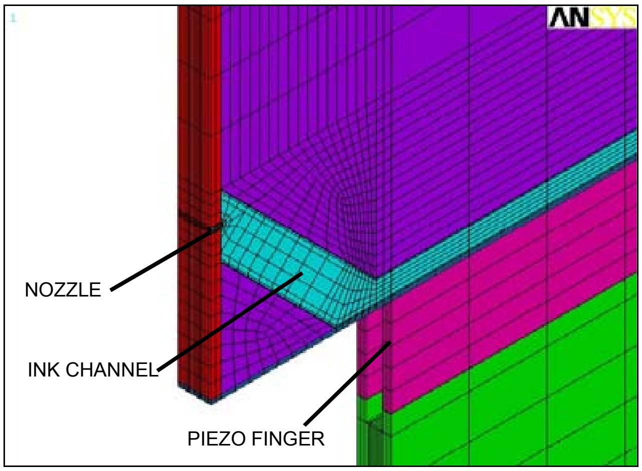

Figure 6: Element distribution near the nozzle and the first part of the channel structure in a half channel module.

4.3 Modeling Drop Formation

A first order approximation of the drop properties is calculated with a mathematical model in Matlab based on a balance of energies [3]. To model the details of the drop formation process we use a 2D rotational symmetric Flow3D model. Both models use the nozzle pressure or flow from acoustic modeling as input.

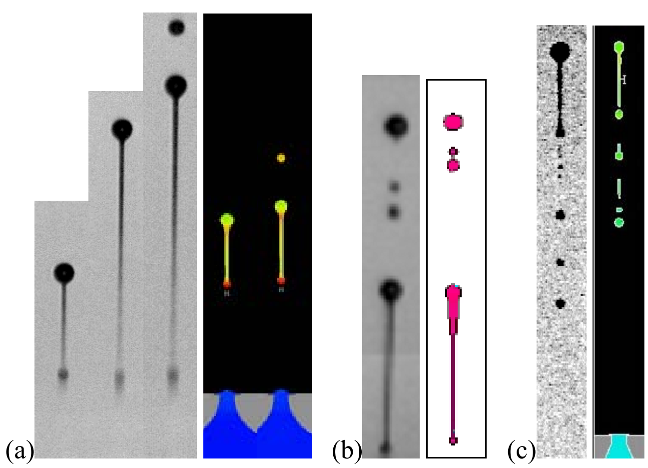

Figure 7: Measured and calculated drop formation at high and low drop speed and repetition rates.

The first part of the drop formation is highly affected by the actuation force. Tail properties and breakup are mainly determined by ink properties as surface tension and viscosity. At higher driving voltage the velocity of the head increases but the tail is not affected at all, Figure 7a, resulting in longer tails at higher drop speed. At very high drop speed, a satellite drop will be formed from the head of the drop. Simulations revealed the mechanism: during the first microseconds of the actuation the acceleration of the ink has to stay below a critical level. Above this level surface tension forces are no longer capable of holding the amount of ink together. In figure 7b the satellite drop formation at high drop repetition rates is shown. The satellite droplets are now formed by breakup of the tail. In Figure 7c the breakup of a very long tail in many small droplets is shown, the Rayleigh instability.

At tail breakup from the meniscus surface a cascade of structures can be seen as described in [4], Figure 8a. Since noise is the source of this structure it is not seen in Flow3D simulations unless the grid is too course giving numerical noise. Exciting a higher order drop formation results in smaller droplets, Figure 8b. Flow3D simulations revealed the mechanism.

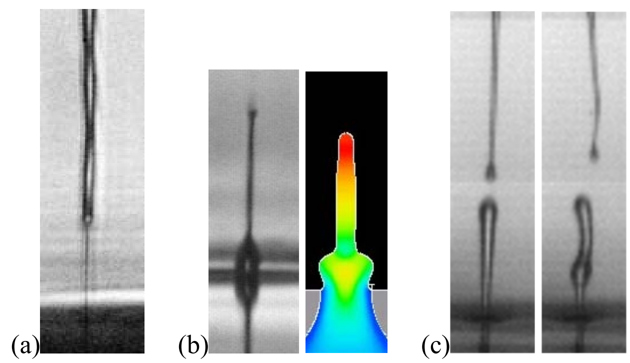

Figure 8: Cascade of structure at tail breakup, higher order drop formation and a distortion of the drop formation

Meniscus movement affects the channel acoustics by changing the reflection conditions in the nozzle region. To model the impact of the drop formation process on channel acoustics and refill an extension of the Flow3D code is developed to include wall flexibility. The obstacle velocity in this version is a function of the local instantaneous pressure. Printhead dynamics are incorporated by means of a relaxation time and acoustic waves are calculated with an adiabatic motion in an ideal liquid. Free surface flow in the nozzle and the acoustics in the ink channels are designed to give a good refill of the nozzle making high drop repetition rates possible.

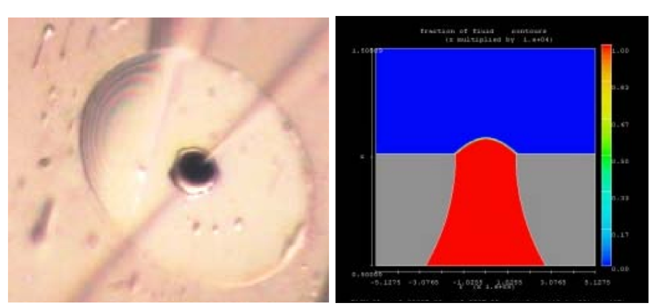

Figure 9: Overfill of nozzle at 10 kHz as measured with a standard camera and simulated with Flow3D.

A strong refill proces however can give overfill at low repetition rates as shown in Figure 9. The overfill situation can result in wetting of the nozzle plate surface. Modeling the wetting phenomena is difficult due to very small contact angles between ink and nozzle plate surface. For a better understanding of the refill mechanism we use mathematical modeling. At short time scales the asymmetric acceleration of the ink due to the variable filling of the nozzle is the main mechanism. This is opposed by resistance terms from viscous, inertial and acoustic coupling effects. At longer time scales capillary forces take over.

4.4 Modeling bubble dynamics

During drop formation, sometimes air is entrapped at the surface resulting in nozzle failure. Air entrapment is always preceeded by a distortion of the drop formation, like by an accidental particle as recorded with the Phantom V7 camera, Figure 8c. Because of the statistical nature of this process no direct Flow3D simulations are done.

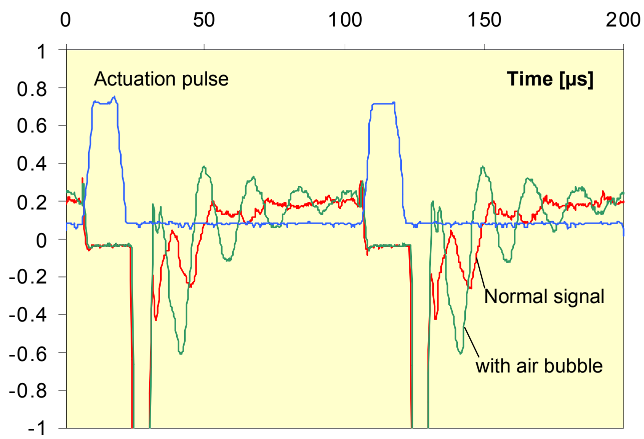

Figure 10: The impact on channel acoustics as measured.

The effects of air bubbles on drop formation can be measured directly. Much more sensitive is the measurement of the change in the acoustics since air bubbles change the reflection conditions at the nozzle. It turns out that starting bubbles are very small, showing only resonances at their Minnaert frequency as can be seen from FFT-analyses of the piezo signal. Also cyclic movement patterns can be seen from principle component analysis. In a large acoustic pressure field air bubbles can grow by rectified diffusion to larger dimensions and will then disturb the drop formation and the basic channel resonance as shown in Figure 10.

Modeling small bubbles and their possible recovery by dissolving or jetting out gives problems with Flow3D because of the very fine grid size needed. Large bubbles can be modeled with adiabatic bubble motion of an ideal gas. An example is shown in Figure 11. Understanding the behavior, growth and displacement of air bubbles in an acoustic field is of major importance for improving the reliability of the drop formation process.

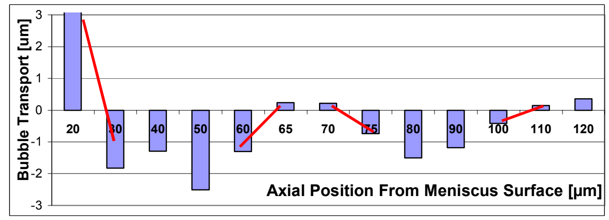

Figure 11: Net bubble displacement as function of axial position of a 10 μm bubble as calculated with Flow3D.

5 FURTHER RESEARCH

We are working now on an analytical model describing the behavior of (small) air bubbles in the nozzle region based on a balance of forces (Bjerknes, drag etc.). On system level we are developing an ILC model [5] based on a chain of two-ports. For understanding the wetting phenomena we need a better model to describe contact line movements with very low contact angles. Because of the very high interation level between all phenomena we continue to look for one complete model, combining detailed CFD calculations with structural simulations.

6 CONCLUSIONS

Modeling in addition to our measurements plays an essential role in understanding the inkjet proces. A major part of the phenomena preceeding drop formation, drop formation itself and the disturbing air bubbles can be well described now, but a lot of work still need to be done.

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