Multiphysics Modelling of a Micro Valve

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Abstract: Electromagnetic micro valves are currently developed empirically or the different physics are treated separately. To accelerate the development-process and for a better understanding of the overall system, a multiphysics simulation is built up. A further objective of this study is to build up competence in modelling complex multiphysics-systems at the Institute of Print Technology.
This simulation considers the electromagnetics, the electronics (including the control of the process), the mechanics and the fluidics with respect to the dependency of these four subsystems to each other. In this way the whole process with the control, the magnetic force generation, the plunger dynamics, the fluid flow and the droplet break up are simulated. To estimate the quality of the model, it is compared to measurements of the electric values and to high speed camera recordings of the droplet break up.

Keywords: Micro Valve, Electromagnetic Actuation, Dynamics, Droplet Break up.

1. Introduction

Electromagnetic actuated micro valves are used in print industry and for automatic dispensing in chemistry applications. They can charge volumes in a range of nano- to microliter per droplet. Figure 1 shows the schematic buildup of a micro valve. The valve has an electromagnetic actuation with a return spring. The fluid is arranged inline trough the electromagnetic part and flows through the nozzle, where the droplet breaks up.

Therefore, the droplet break up has a wide influence on the quality of the process, for example on the droplet volume or on the occurring of satellite droplets. The droplet break up itself depends on the electrical control circuit, the electromagnetic circuit with the magnetic force generation, the geometry of the valve (plunger, seating and nozzle), the wall wetting and the rheological properties of the fluid.

Presently, the different parameters are specified experimentally in long-winded tests. Thereby a new prototype has to be fabricated for each test and the physical behavior is not known very well.

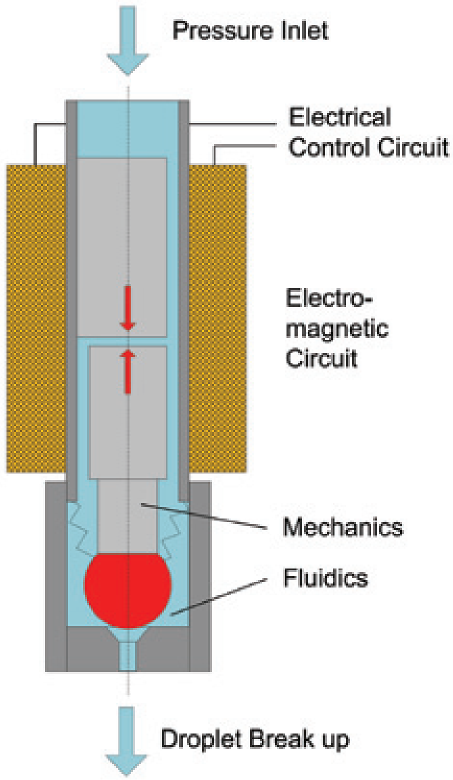

Figure 1. Schematic buildup of a micro valve

The goal of the study is to specify the parameters of any valve type using multiphysics simulation without manufacturing prototypes for every parameter evaluation. Moreover, a better understanding for the physics will be achieved, on the one hand for the valve development and on the other hand for the dispensing and printing applications.
Another goal is the building up of general competence in modelling any complex multiphysics system.

2. Modelling

To accurately represent the whole micro valve system from the valve control circuit to the droplet flight, the system is divided into four subsystems.

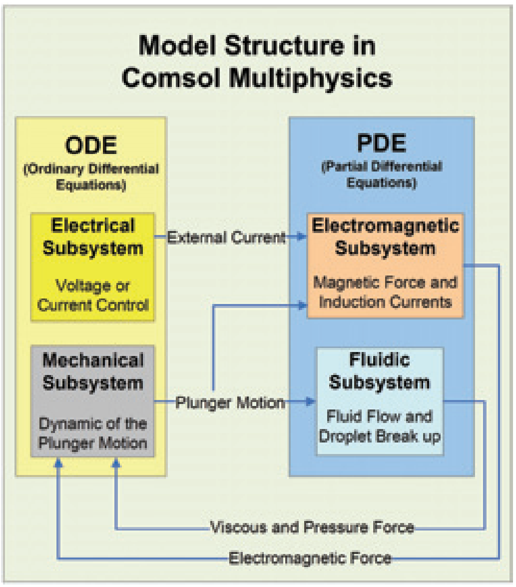

Figure 2. Model structure of the micro valve simulation

2.1 Electrical Subsystem

In the electrical subsystem, the valve control circuit is implemented by modelling a time-dependent voltage. This voltage is the input for the electromagnetic subsystem, and defines the length of the valves opening time.

2.2 Electromagnetic Subsystem

The electromagnetic subsystem is a transient analysis in the azimuthal induction currents, vector potential mode. The occurring induction currents from self-induction and from the variation of the magnetic potential (due to magnetic circuit variation caused by the plunger motion) are considered. The induction currents caused by the Lorenz field are neglected.
To respect the nonlinear magnetic material behavior, a measured B-H curve is implemented to compute the correct magnetic flux density. Out of that, the magnetic force on the valve plunger can be computed appropriate at each time-step. This force is handed over to the mechanical subsystem.

2.3 Mechanical Subsystem

In the mechanical subsystem the dynamic of the plunger motion is described by an ODE-formulation considering the forces on the plunger from the electromagnetic and the fluidic subsystem as well as the mechanical parts like the spring and the mechanical stop positions. It connects the electromagnetic and the fluidic subsystem by computing the position and velocity of the plunger at each time-step.
In the electromagnetic subsystem, the position of the plunger defines the air gap and has therewith influence on the magnetic force and the induction currents.
For the fluidic subsystem, the plunger position defines the opening and closing of the valve's cross section. The plunger velocity has influence on the shear forces in the fluid. So the plunger position and velocity have a wide influence on the fluid flow.

2.4 Fluidic Subsystem

The fluidic subsystem is modeled with a two-phase flow, laminar, phase field, weakly compressible, transient analysis.

Because of the small nozzle diameter, cavitation occurs in the entrance of the nozzle. To avoid the pressure from falling under vacuum, what would mean a serious inaccuracy for the whole process, the flow is assumed as weakly compressible with a formulation to increase the density and therewith the volume of the fluid locally, where the low pressure would make evaporate the fluid. This formulation is not a full thermodynamic model, because the evaporation itself is not of interest in this study. Yet, it explains in which areas cavitation is to be expected and respects its influence on the main process.
The changing of the opening cross section is modelled by ALE. The mesh displacement is ruled by the piston motion of the ODE formulation of the mechanical subsystem.
As soon as the valve is fully open, the fluid begins to flow through the nozzle and reaches the tearing edge where the fluid will flow out and a droplet will be generated. Beside the geometry of the nozzle and the tearing edge, the droplet

break up depends on the rheological properties of the fluid like viscosity, surface tension forces, and wall wetting, which can all be modeled appropriate in Comsol Multiphysics.

4. Results

4.1 Electromagnetic Subsystem

Figure 3 shows the magnetic flux density in the electromagnetic system at a specific time-step. The magnetic circuit is closed over the housing of the coil. The maximal flux density is in the air gap to generate the electromagnetic force.
Figure 4 shows the induced current density at the same time-step. The induced currents occur first and foremost in the coil, but also in the housing of the coil. This induction current limits the total current in the coil and therewith the step-up of the magnetic force.
Figure 5 illustrates the process of the electromagnetic system. I_{Extern} is the current, which theoretically results from the applied voltage at the Coil. $I_{Induction}$ is the induced current in the coil caused by self-induction and from the variation of the magnetic potential caused by the plunger motion. I_{Total} is the resulting current in

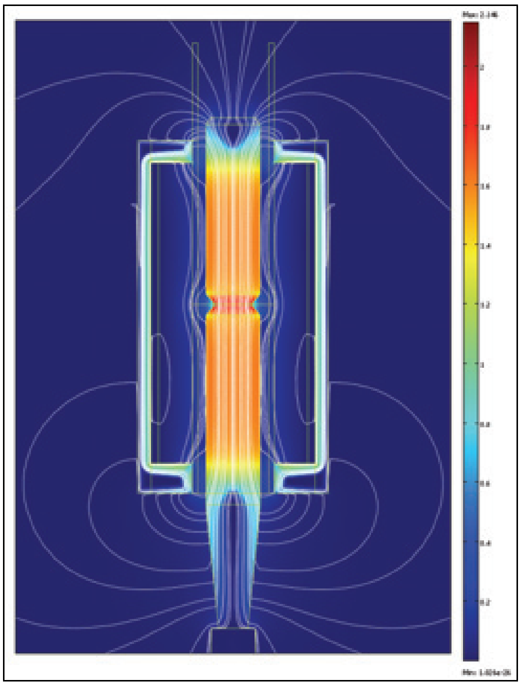

Figure 3. Electromagnetic: Surface: Magnetic flux density, norm [T]. Streamlines: Magnetic flux density.

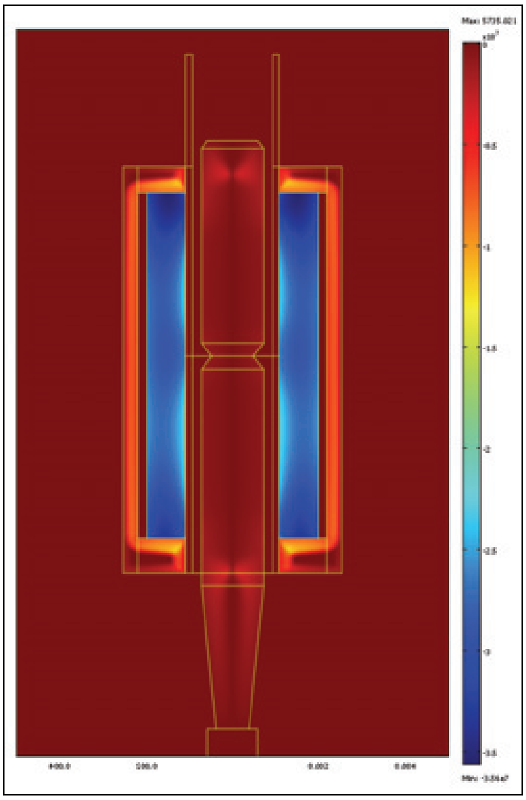

Figure 4. Electromagnetic: Surface: Induced current density, phi component [A/mm^2]

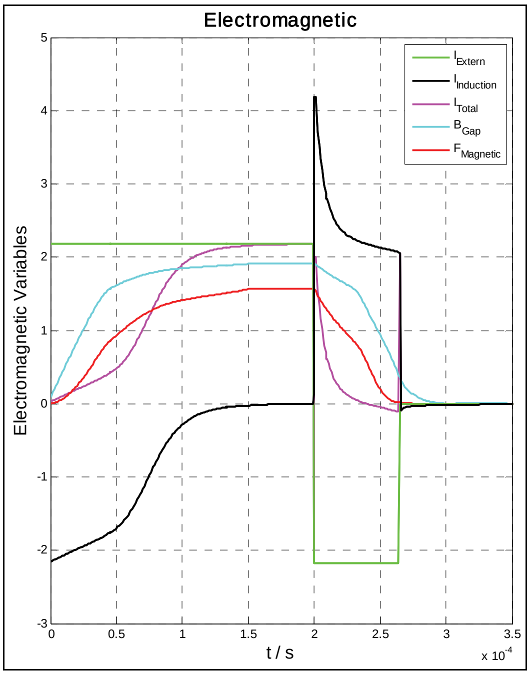

Figure 5. Electromagnetic

the coil.
The magnetic flux density in the air gap B_{Gap} increases quite fast in the first section, until the saturation of the magnetic material is reached. The magnetic force on the plunger follows widely to the magnetic flux density in the air gap.

4.2 Plunger Motion

Figure 6 shows the motion of the plunger as a result of the mechanical system. Therefore the force of the spring F_{Spring}, the magnetic force $F_{Magnetic}$ the force from the pressure $F_{Pressure}$ and the fluidic shearing force $F_{Viscous\ Stress}$ are shown. Thereby, $F_{Viscous\ Stress}$ reaches quite remarkable values. The sum of these forces of the different subsystems is the total force on the plunger $F_{Plunger}$ which accelerates the plunger. In this way, the motion is computed with the ODE formulation. Therewith, the opening and closing times, the opening cross section and the influence of the plunger motion on the fluid is respected appropriate in the fluidic subsystem.

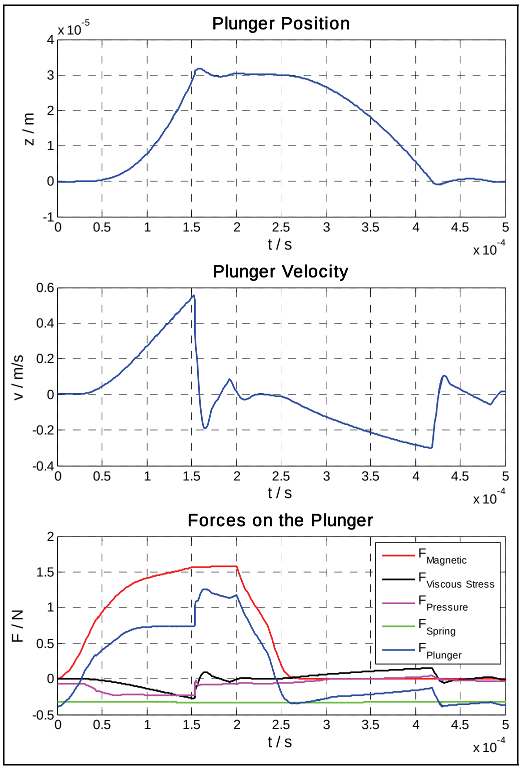

Figure 6. Motion of the plunger

4.3 Fluid in the Nozzle

Figure 7 shows the behavior of the fluid in the nozzle. The red area is the liquid fluid and the blue area is air.
At the opening (sequence 1 to 3 in figure 7), as long as the plunger moves, the fluid cannot flow out of the nozzle, because the plunger moves quite fast and draws the fluid backward. The stroke of the plunger is quite small, but visible (modeled with ALE).
Because the nozzle is very thin, the pressure falls down until the fluid locally evaporates, as shown in figure 8.
When the plunger stops when reaching its end position, the fluid can flow out. The fluid on the wall of the nozzle keeps its position, while the fluid in the middle flows outward (sequence 4 to 6 in figure 7). As a result, the fluid flows pointed out of the nozzle (sequence 7 to 9 in figure 7).

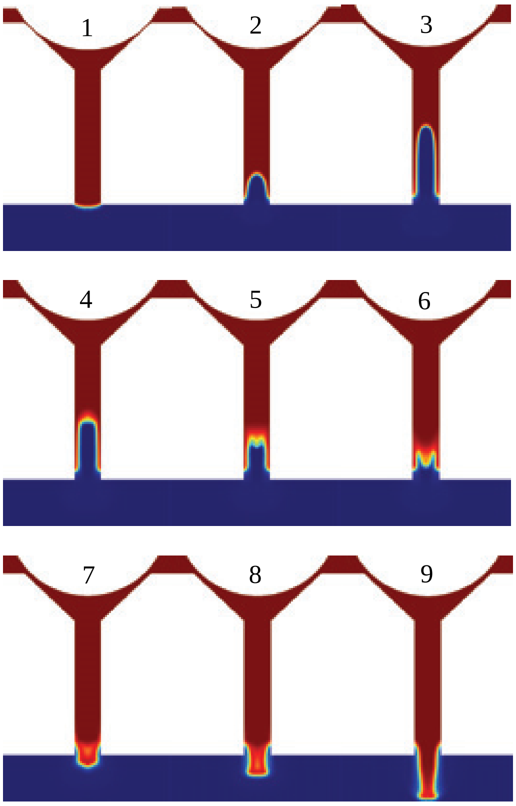

Figure 7. Sequences of the fluid in the nozzle

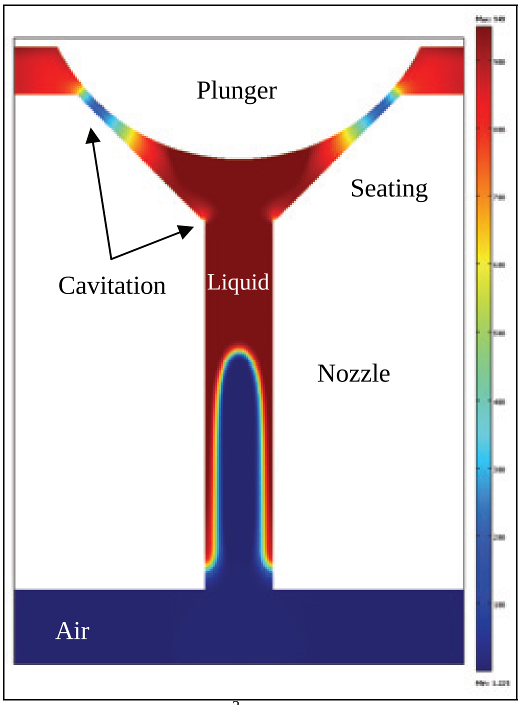

Figure 8. Density [kg/m^3]: Cavitation in the nozzle

4.3 Droplet Break up

As the study is still running, the simulation results of the droplet break up could not be finished until the deadline of this paper. Figure 9 shows the first few sequences of the droplet break up. Because of the pointed outflow, a small satellite droplet begins to break up, corresponding to the first two sequences of the high speed camera recording in figure 11.

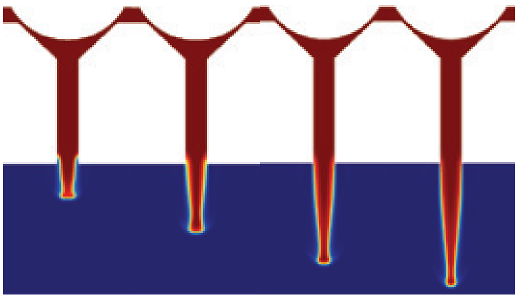

Figure 9. First sequences of the droplet break up

As a reference a droplet break up with satellites is shown in the appendix in figure 12 for a case with a wider nozzle. This case is a lot easier to reach convergence.

5. Experimental Results

5.1 Verification of the Electromagnetic

As a result of the small dimensions, the electromagnetic force could not be measured for this study. As a simple verification, the current is logged during a valve switching. In figure 10, the experimental result is compared with the simulation of the coil current. The opening time fits very well and also the characteristic is very similar.

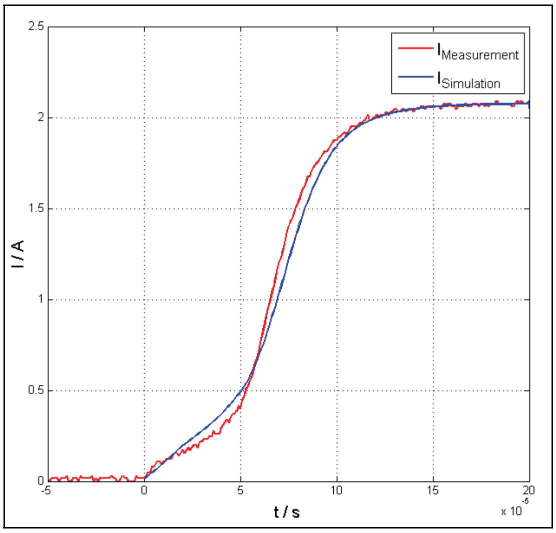

Figure 10. Measured and simulated current in the coil

5.2 Recording of a Droplet Break up
To verify the fluidics, a droplet break up is recorded by a high speed camera.

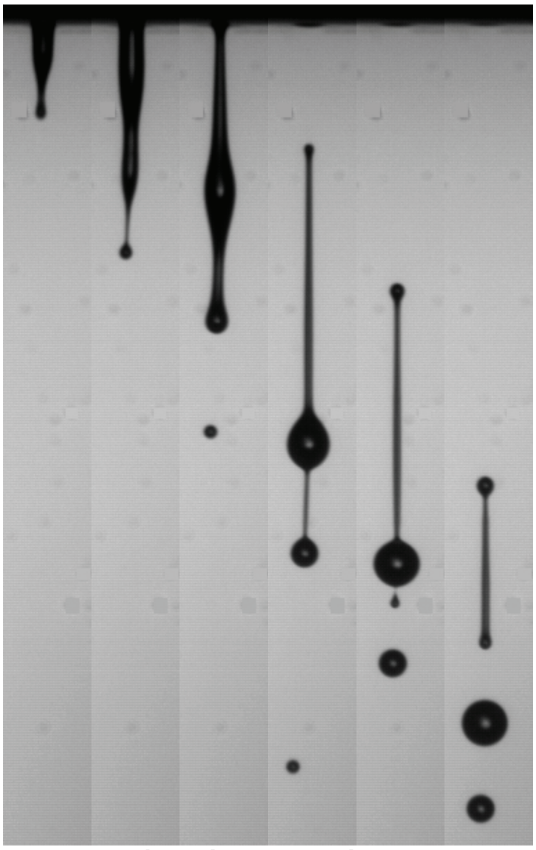
Figure 11. High speed camera recording

The first eye-catching aspect is that the droplet is not as symmetric as in the simulation, where the symmetry is ideal.
In the first sequence, the droplet is already rather pointed, because of the fact, that the fluid is first drawn back into the nozzle. Therefore, a very small droplet breaks up from the main droplet.
After that, the trail of the main droplet definitely breaks up from the nozzle. The main droplet narrows down and a second small droplet is separated. Finally, the trail separates from the main droplet.
This behavior for the droplet break up is reproducible.

5. Discussion

The simulation comes quite near to the reality and would certainly accelerate the process of new valve developments by building prototypes, which are already very close to the requirements. The desired accuracy is always in competition to the buildup time and the computing time of the simulation, especially in the fluidics with two phase flow, cavitation effects and satellite droplets.
The better understanding of the whole system will help to consider all aspects and to know which parameters have to be tuned to reach a specific requirement. Thereby, it could be verified, that the different aspects can only be modelled appropriately if their dependency on each other is respected. For example, the dynamic of the plunger motion has a strong effect on the fluidic system like cavitation or the backflow of the fluid in the nozzle. In the other direction, the forces out of the fluidic and the electromagnetic system influence the dynamics of the plunger.
The buildup of such an overall simulation is rather time consuming, at least for the first time. All the settings including the solver parameters have to be set very carefully to reach convergence. So the buildup of a simulation like this is wise, if it can be used for several products or projects. If not, the costs may be a bit too high.

6. Future Work

The model will be verified further on for different parameters. The fluidic subsystem will be computed in 3D to estimate the difference to the 2D axial symmetry simulation.
This multiphysics simulation will also be a basis to model any valve in a fast way with reliable results.

7. Conclusions

An overall simulation of an electromagnetic actuated micro valve is built up, considering the different aspects from the valve control to the droplet break up. The quality of the model is verified by measurements and high speed camera recordings of the droplets. Moreover, the understanding of the whole system and the influence of the different parameters is increased. Furthermore, a step forward in building up competence in multiphysics simulations in the Institute of Print Technology is done.

8. References

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9. Acknowledgements

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10. Appendix

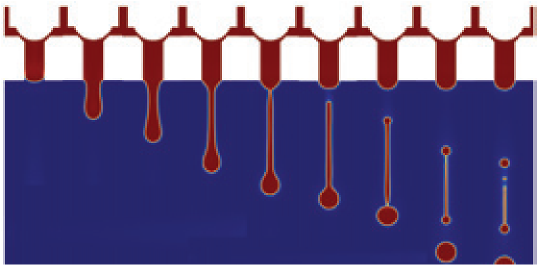

Figure 12. Droplet break up with wider nozzle

Figure 12 shows a droplet break up with satellites for a case with a wider nozzle.