Modeling and Numerical Simulation of the Crosstalk Behavior of a DOD Printhead

Hermann Seitz
research center caesar
Bonn, Germany

Abstract

This paper reports the modeling of a given printhead with piezoelectric bend mode actuators. The model describes the electric, mechanical as well as the fluid dynamic characteristics of the printhead. The electric and mechanical parts of the piezoelectric bend mode actuator are described by conventional lumped elements which interact as constituent parts of a Kirchhoffian network. The complex three-dimensional fluid analysis is performed by a commercial computational fluid dynamics (CFD) free-surface modeling package. The fluid structure coupling is realized by exchanging of data between the electro-mechanical model and the fluid simulation tool for every numerical time step.

The piezoelectric printhead has been computationally simulated to analyze the fluid flow dynamics and the jet forming process. Moreover inter-channel crosstalk caused by interconnected fluid channels of the printhead is studied. As a result, this paper discusses the fundamentals of the crosstalk problem and shows ways for crosstalk compensation methods based on optimized compensation drive pulses.

Introduction

Printheads have found extensive application in ink jet printing systems. Furthermore there is a growing demand for using the ink jet technology in a wider range of applications. For this reason a DOD printhead has been developed that can be run with not ink-based medias like waxes, oils, adhesives, fuels, lacquers etc.

The basic description of the printhead with piezoelectric bend mode actuators has been given in a patent.[1] An improved version of the printhead has been presented by Kretschmer.[2] In Kretschmers paper it was shown that the problems of the original type of printhead like crosstalk with neighboring channels, low working frequency etc. can be overcome by the use of a new multilayer piezoceramic material and by walls placed between the single bend mode actuators. This new design of the printhead is, however, quite difficult to manufacture and limits the number of nozzles per inch. This paper deals with the original design of the printhead without channel walls and discusses how to analyze and to solve the described problems, especially the negative effects of crosstalk by means of numerical simulations.

Printhead Design

The printhead design is based on three main components: the nozzle plate, the bend mode actuators and the chassis. The nozzle plate has a row of very small, precise nozzles with conical shape. An actuator is assigned to every nozzle. A flexible connector board supplies the actuators with the electric drive signals. This assembly is covered by the chassis that has the function of a fluid chamber to provide the actuators with fluid. Each of the actuators can be run independently from the remaining actuators. The bend mode actuators are fixed at one end. The nozzles are placed under the free ends of the actuators.

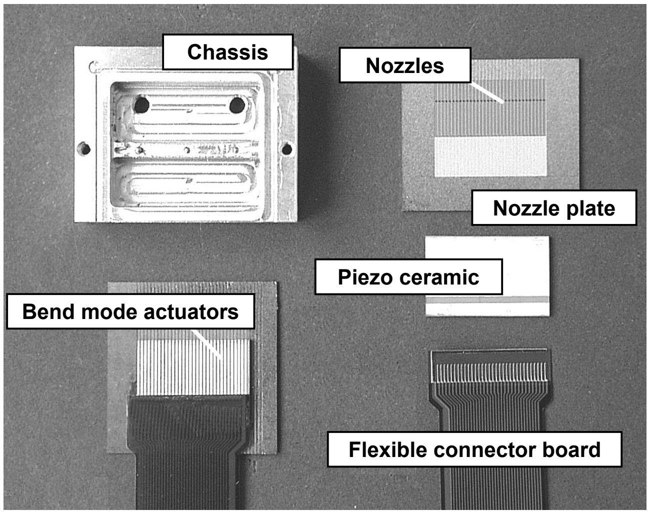

Figure 1. Basic printhead components and assembly

Figure 1 illustrates the components of the printhead. The printhead is a prototype that has been manufactured at the FGB, TU München. The printhead is the key component of a new solid freeform fabrication technology.[3] This new technology can be used to fabricate physical objects directly from CAD data sources using the printhead to deposit droplets of wax. Since this wax has a high melting point the printhead must be heated up to 130°C to melt the wax. Table 1 lists the basic technical data of the printhead.

Table 1. Technical data of the printhead

Number of nozzles	32
Viscosity of the fluid	0.7 – 20 mPa s
Temperature range	20 – 130 °C
Nozzle pitch	50 dpi
Nozzle diameter	50 μm
Continuous frequency	5 kHz
Supply voltage	55 V

Drop Generation

The drop generation is shown in Figure 2. After applying the drive pulse, the bend mode actuator deviates at its free end away from the nozzle plate, so the fluid can flow in the gap between the bend mode actuator and the nozzle plate. After switching off the pulse, the actuator relaxes rapidly towards the nozzle plate and forces the liquid through the nozzle. The resulting droplet moves perpendicularly away from the nozzle plate. Piezo bend mode actuators combine a high deflection with a high velocity of the actuator. Due to that it is possible to jet a wide range of fluids.

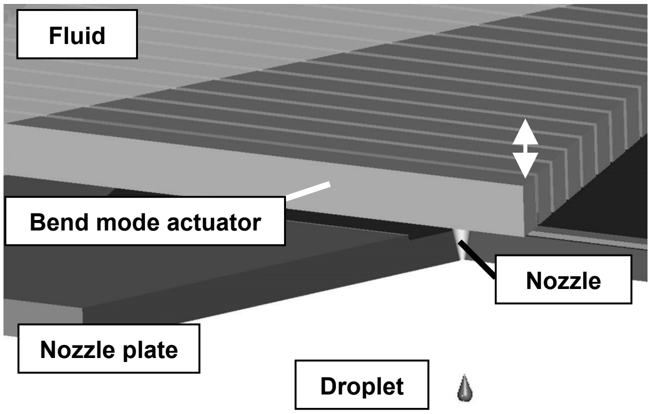

Figure 2. Function principle of the DOD printhead

Since the bend mode actuators are aligned very closely and the actuators are not decoupled by a constructive design feature like channel walls there is a very strong crosstalk between neighboring channels through the fluid. In our case crosstalk causes an unwanted drop generation at the adjoining channels although these adjacent channels are not fired (see Figure 3) as well as drop velocity and volume variations if two adjacent channels are fired. These effects lead to a bad printing and image quality and decrease the performance of the printhead.

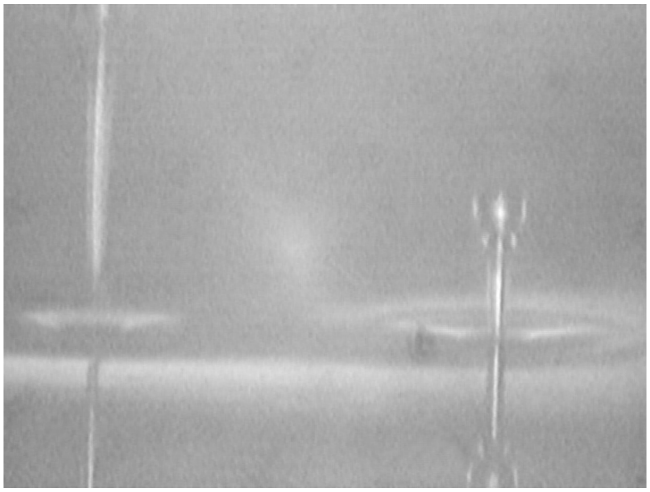

Figure 3. Only the left channel is fired but also the right channel ejects a droplet because of the crosstalk effect.

Modeling

Due to the complexity of the printhead, the system has to be separated into partitions. Based on a definition of Zienkiewicz,[4] the model of the printhead consists of three coupled systems: a coupled electric and mechanical system that describes the actuator and the fluid system. Since there are strong interactions between the electric and mechanical system as well as between the mechanical system and the fluid, the resulting differential equations of the three systems can not be solved separately.

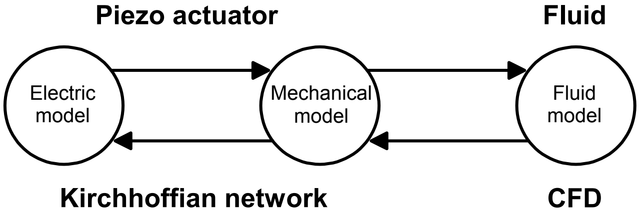

Figure 4. Printhead described as a coupled system

Experiments have shown that the piezoelectric bend mode actuator can be modeled by a quite simple equivalent network. Using electrical analogies it is possible to include the electric part as well as the mechanical part of the actuator within one network. The model consists of lumped elements which describe the electric and mechanical parameters. The complex three-dimensional fluid analysis is performed by the commercial computational fluid dynamics (CFD) package FLOW-3D. The coupling of the electro-mechanical model and the fluid model is realized by exchanging the data between the two systems.

Actuator Model

In order to study the dynamic response of the actuator when applying a driving signal, the oscillation of the actuator without surrounding fluid was measured with a laser vibrometer (see Figure 5).

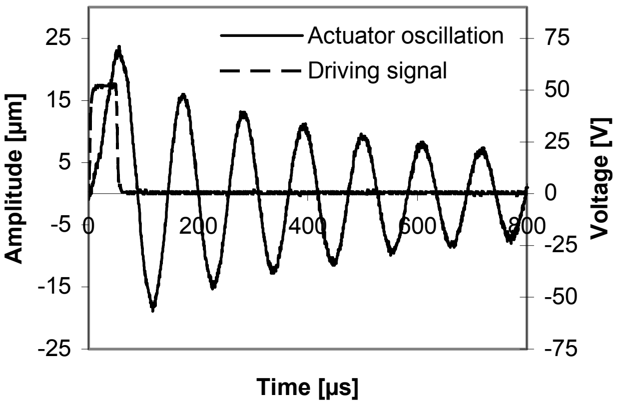

Figure 5. Oscillation of the actuator without surrounding fluid

The measurement demonstrates that the actuator can be regarded as a one-mass oscillator. On the electric side the piezo actuator is approximated as a electric capacitance. This results in a lumped parameter model of one single actuator as illustrated in Figure 6.

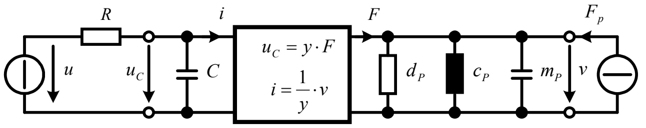

Figure 6. Lumped parameter model of the piezo actuator (electro-mechanical model)

Every single bend mode actuator and thus the electro-mechanical part of the printhead is modeled as an equivalent electric circuit with lumped elements. The model consists of two parts. On the one hand, the electric part with the capacitor C, representing the electric capacitance of the piezo ceramic, the drive pulse voltage source u and the series resistance R. On the other hand, the mechanical part consisting of a one mass oscillator model with the mass m_P, the stiffness c_P and the damping d_P. The coupling of the electric and mechanical part is realized by a gyrator that transforms the electric parameters current i and voltage u_C into the mechanical parameters force F and velocity v of the actuator using the equations:

$$i = \frac{1}{y} \cdot v \tag{1}$$

$$u_C = y \cdot F \tag{2}$$

The parameter y describes the coupling between electric and mechanical fields in the piezo ceramic. The force F_P is the integrated pressure force of the fluid on the actuator. Force F_P and velocity v are also the coupling variables between the electro-mechanical system an the fluidic part. The presented Kirchhoffian network yield to a system of linear differential equations. All the parameters of the model are either given or are obtained by analyzing the dynamic response of the actuator on a drive pulse (see Figure 5).

Fluid Model

Crosstalk effects affect not only the first neighbors of a fired channel but also the second neighbors. As a consequence a three-dimensional flow region with five actuators has been defined in order to investigate the crosstalk behavior between the channels through the fluid. Two more fixed actuators with half width describe realistic boundary conditions on the left and right side of the flow region (see Figure 7).

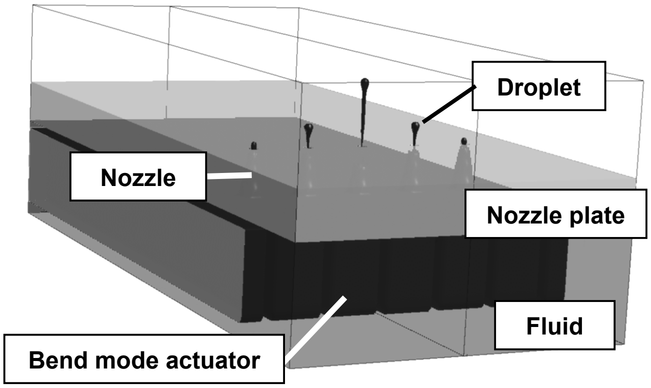

Figure 7. Three-dimensional flow region with five active actuators and two fixed actuators defining the boundary conditions

The software package Flow-3D was chosen to analyze the fluid flow in the defined three-dimensional region. Flow-3D is capable of handling both a free surface which is necessary to simulate the drop formation process and moving obstacles that are used to define the deformable actuators. Each actuator consists of ten obstacles which deflect according to the lowest eigenmode of a single clamped beam, i.e. the obstacles move according to their position in the beam. This behavior of the actuator was experimentally corroborated.

The parameters of the fluid (diethylsuccinate) that was used for validation tests in the real printhead are also used for the fluid model.

The fluid structure interaction was realized by exchanging of data between the electro-mechanical model and the fluid simulation tool for every numerical time step. A staggered solution procedure[5] was chosen to solve the coupled system.

Crosstalk Analysis and Compensation

In a first step the phenomena of crosstalk is investigated. Different combinations of driven and passive channels are simulated and analyzed. In the normal case with one driven channel the jetted droplet has a velocity of v = 6.5 m/s. The two neighboring channels also eject droplets because of crosstalk effects with a velocity of v = 1.6 m/s. The second neighbors only show a slight oscillation of the fluid in the nozzle. This case is illustrated in Figure 8.

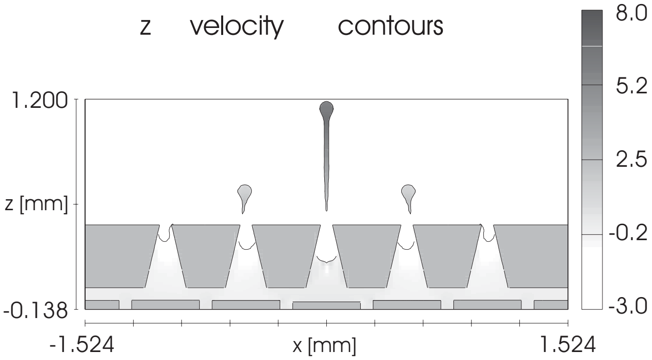

Figure 8. Crosstalk at the neighboring channels when the middle channel is driven and there is no compensation

If two adjoining channels are driven, the velocity of the droplet increases to v = 9.5 m/s. If three neighboring channels are driven at the same time the velocity of the droplet in the middle is v = 12.8 m/s and the velocity of the remaining two droplets is v = 10.5 m/s. In both cases there are also droplets ejected at the non-driven channels because of crosstalk. Furthermore, the droplet volumes differ according to the number of adjacent driven channels. Since different velocities and volumes of the droplets lead to a poor printing quality these facts cannot be accepted. As a consequence, the channels of the printhead have to be fired in three groups. On the one hand, this avoids the problems of crosstalk between adjacent driven channels. On the other hand, there is only one case of crosstalk remaining that has to be considered – the case with one driven channel. Another negative consequence is that the driving frequency is decreasing.

The analysis of the fluid in the neighboring nozzle of a driven channel shows a flow similar to the fluid flow in the nozzle of the driven channel (see Figure 9). This leads to the idea that the crosstalk can be reduced by applying a phase shifted compensations impulse at the neighboring channels. Consequently a parameter study was carried out that investigated three different phase shifted compensation pulses:

- a single pulse with constant voltage and variable pulse width
- a singe pulse with constant pulse width and variable voltage
- a double pulse with constant voltage and variable pulse width

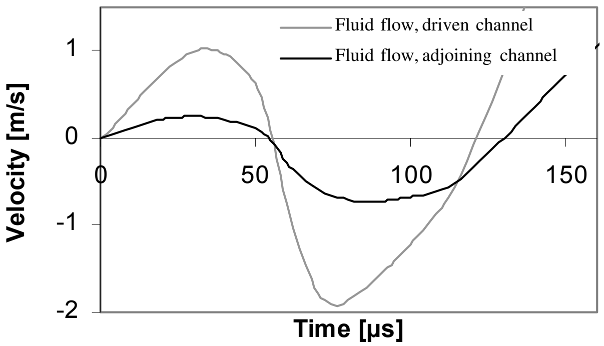

Figure 9. Fluid velocity in the nozzles of the driven and the adjoining non-driven channel

Another important parameter that has to be consider is the delay between the driving pulse and the compensation pulse.

The results of the parameter study is that there is a sufficient compensation in only one case with the double pulse. In the other two cases there is still an ejection of droplets at the neighboring channels because of crosstalk effects even with optimized pulse parameters. The compensation effects of the case with double pulse is shown in Figure 10.

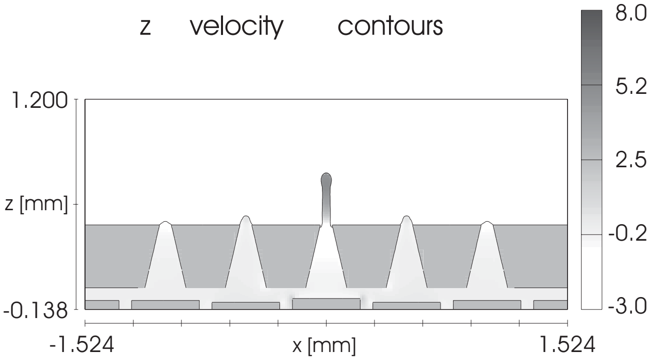

Figure 10. Maximum crosstalk at the neighboring channels if these channels are compensated with the optimized double pulse

The double compensation pulse prevents the neighboring channels from ejecting a droplet. But there is still an oscillation of the fluid in the neighboring channel. The compensation has also negative effects on the driven channel. The droplet velocity decreases to v = 4.7 m/s.

The effect of compensation is illustrated in Figure 11. The velocity of the fluid inside the nozzle of the compensated channel that normally causes the unwanted jetting is decelerated and thus prevents the nozzle from ejecting a droplet.

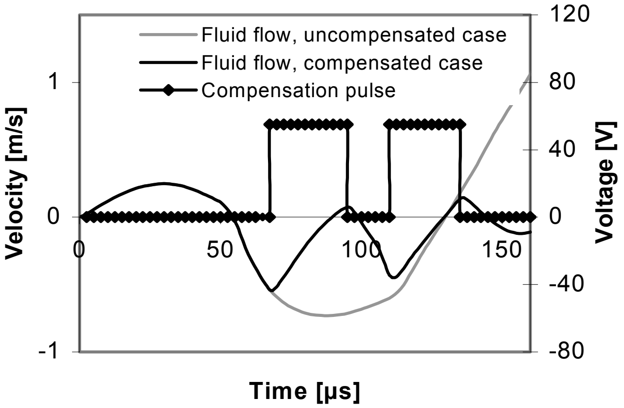

Figure 11. Fluid velocity in the nozzle of the neighboring channel in the compensated and uncompensated case

Conclusion

A CFD model for the 3D analysis of the fluid flow in a given printhead has been combined with a electro-mechanical lumped parameter model of the piezo bend mode actuator to study the crosstalk behavior between adjoining channels. A parameter study has been carried out to study the different ways of crosstalk compensation.

The only way to prevent the closest neighbors of a driven channel to eject a unwanted droplet is to apply a double pulse with optimized parameters at the affected channels.

This way of compensation has two negative effects: Applying a compensation pulse not only prevents the unwanted jetting but also reduces the velocity of the ejected droplet at the driven channel. Another negative consequence is that the driving frequency is decreased because the channels of the printhead must be fired in three groups.

Moreover the modeling of the given printhead described as a coupled system makes it possible to understand the underlying mechanisms of the drop generation process as well as the crosstalk behavior an thus can be used as a tool for a further optimization of the printhead.

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Biography

Hermann Seitz studied electrical engineering at the TU München, Germany and received his diploma in 1997. From 1997 to 2001 he was a research associate at the TU München. His main research area was on drop-on-demand printhead technology. He received his Dr.-Ing. from the TU München in 2002. Since 2001 he is leading the research group Rapid Prototyping at the research center caesar in Bonn, Germany. His major focus is on the development of new innovative ink-jet based rapid prototyping techniques for medical applications.