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Research paper

A waveform design method for piezoelectric inkjet printhead with Doppler vibration test and numerical simulation

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ABSTRACT

Piezoelectric inkjet printing technology has been widely used in recent years. A new method for driving waveform design was presented to overcome the limitations in traditional waveform design methods. In this paper, the Doppler vibration test was used to determine the time of voltage rising and falling section. According to the superposition principle of velocity wave, the time of voltage dwelling section was determined by the numerical simulation. The optimal parameters with $t_{rise} = 5\,\mu s$, $t_{dwell} = 16\,\mu s$ and $t_{fall} = 3\,\mu s$ of unipolar trapezoidal driving waveform was obtained. By using this method, the number of experiments can be significantly reduced in the initial stage of the printhead development process. The experimental results proved the feasibility of this method.

1. Introduction

Piezoelectric inkjet printheads not only have strong control ability for ink droplets and high printing accuracy, but also need no heating, so they have more flexibility in the ink compatibility [1]. Whether in traditional printing industry, additive manufacturing or in cell printing and other fields, the piezoelectric inkjet technology has been widely used. In different applications of piezoelectric inkjet printheads, driving waveform directly control the volume and velocity of the droplets [2]. Many researchers have proposed different ways for designing the driving waveform to achieve the desired jetting performance.

Bogy et al. proposed the propagating theory of pressure wave and considered that the optimum pulse width of the driving waveform is L/C, in which L is the length of the pressure chamber and C is the velocity of sound in the ink [3]. However, the velocity of sound in liquid is closely related to the geometry of the channel and the stiffness of the channel wall, which is difficult to be obtained directly [4,5]. Kye-Si Kwon et al. considered that the period of the residual pressure oscillation in the chamber is same as the PZT self-sensing signal [6]. However, a detailed analysis of the pressure wave propagation has not been conducted because the physical phenomena in inkjet printing processes are complicated [2]. What's more, an additional circuit for measuring the pressure-wave signal needs to be implemented, which may be difficult for some commercial piezo inkjet printheads [7]. Wassink et al. proposed an iterative learning control (ILC) method to optimize the actuation pulse [8]. Amol A. Khalate et al. proposed an optimization-based feedforward control method using a discrete-time transfer function derived from the narrow-gap model [9]. However, assumptions and simplifications are often introduced in the establishment of analytical models, which resulted in lower accuracy.

In this paper, a new method of driving waveform design for piezoelectric inkjet printhead was proposed. The optimal parameters were determined by a combination of Doppler test and numerical simulation. The number of experiments and simulations can be obviously reduced by using this method. In addition, the multi-physics direct bidirectional coupling model in COMSOL Multiphysics software is more accurate than that in the analytical model, which is suitable for most piezo inkjet printheads.

2. Experimental system and numerical simulation model

2.1. Experimental system

Fig. 1 shows the structure of the piezoelectric inkjet printhead fabricated by the micro-electro-mechanical systems (MEMS) technology with the vibration plate of SiO_2, the piezoelectric material of $Pb(Zr_xTi_{1-x})O_3$ (PZT) and the chamber of SU-8 photoresist (MicroChem Corporation, Newton, MA, USA). The schematic diagram of the experimental system is shown in Fig. 2. The arbitrary waveform generator (DG1022U, RIGOL, China) is used to output the driving waveform. The amplifier (HA-405, PINTEK, Taiwan, China) amplifies the waveform to the appropriate voltage and loads it on the piezoelectric actuator. A

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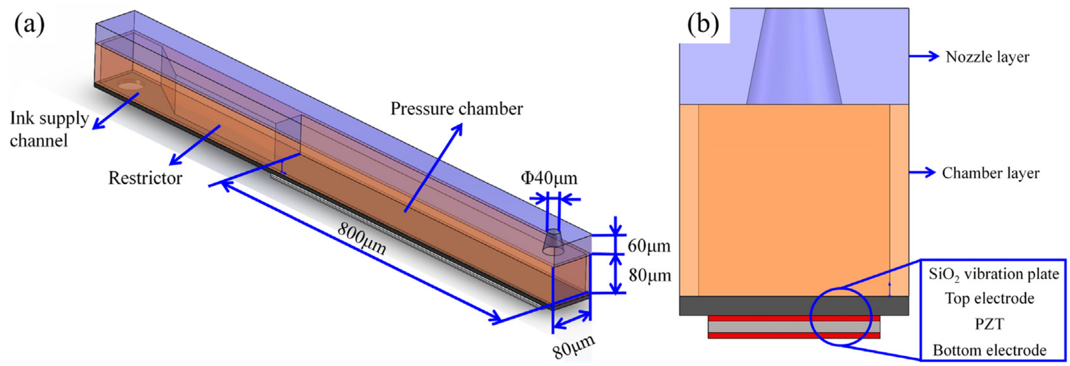

Fig. 1. 3D model of the piezoelectric inkjet printhead, (a) axonometric drawing, (b) right side view.

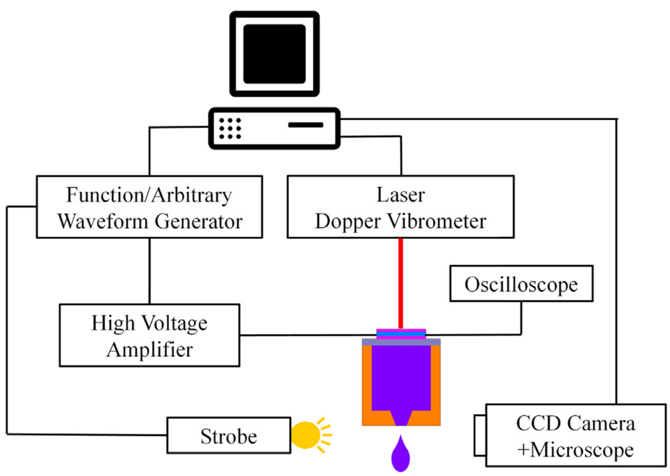

Fig. 2. Schematic diagram of the experimental system.

CCD camera with a microscope (ARTCAM-445KY2, SONY, Japan) and a LED flashing light synchronized with the jetting signal are used to capture the formation process images of droplets. The inkjet test system uses edge detection technology to measure the droplet profile so that the speed and volume of the droplet can be calculated. The specific value of the voltage between the top and bottom electrodes of the piezoelectric actuator is achieved from the oscilloscope (DS1000U, RIGOL, China). The laser Doppler vibrometer (VDD-E-600/OFV-534, Polytec, Germany) is used to measure the displacement of the piezoelectric actuated vibration plate.

2.2. Numerical simulation model

The model which was built in COMSOL Multiphysics (COMSOL 4.3a, COMSOL Inc., Sweden) is shown in Fig. 3. The model involves the coupling of piezoelectric field, solid mechanics field, fluid mechanics field and gas-liquid two-phase flow. For bidirectional fluid-structure coupling, the real-time boundary data is transferred between two physics fields. So, the velocity of the piezoelectric actuated vibration plate is set as the inlet velocity of the fluid field and the fluid pressure as the boundary load of the vibration plate on the fluid-structure coupling surface. In addition, the moving grid method is used to deal with the large-size deformation of the structure and the fluid-structure interface construction in this paper. In the gas-liquid two-phase flow study domain, the level-set method is used to describe the topological structure changes of the fluid in jetting process.

The Navier-Stokes equation [10] for incompressible fluid in the chamber is as following.

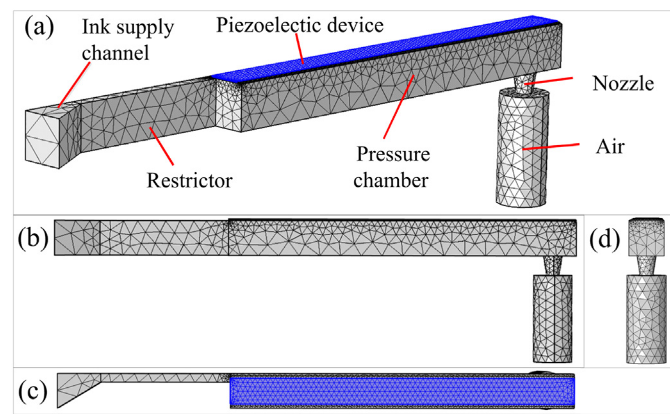

Fig. 3. Numerical simulation model built in COMSOL Multiphysics, (a) axonometric drawing, (b) front view, (c) top view (d) right side view.

$$-\frac{1}{\rho}\nabla p+\frac{\mu}{\rho}\nabla^2\mathbf{u}+\mathbf{F}=\frac{\partial\mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u} \tag{1}$$

where ρ represents the density of liquid (kg/m^3), p represents pressure (Pa), μ represents the dynamic viscosity (N·s/m^2), $\mathbf{u}$ represents fluid velocity (m/s), ∇ is the Hamiltonian operator, $-\frac{1}{\rho}\nabla p$ is the pressure difference of unit mass fluid, $\frac{\mu}{\rho}\nabla^2\mathbf{u}$ is the viscous force, $\mathbf{F}$ is the volume force and $\frac{\partial\mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}$ is the acceleration which includes local acceleration and migration acceleration.

In the study of the laminar two-phase flow, the transfer equation of the level-set function used to track the position of the interface [11] is as following.

$$\frac{\partial\phi}{\partial t}+\nabla\cdot(\phi\mathbf{u})+\gamma\left[\left(\nabla\cdot\left(\phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right)\right)-\varepsilon\nabla\cdot\nabla\phi\right]=0 \tag{2}$$

where ϕ is the level-set function which is defined as 0.5, 0, 1 in interface, air and ink, respectively. The interface moves at the fluid velocity $\mathbf{u}$. ε is proportional to the thickness of the transition layer, which is set as half of the typical mesh size in the region passed by the droplet for normal models. γ determines the amount of reinitialization. The suitable value of γ is the maximum value occurring in the velocity field.

The parameters of ink set in the model are same as those used in experiments. The viscosity is 2 mPa·s (20 °C), the density is 1050 kg/m^3 and the surface tension is 0.045 N/m (20 °C).

3. Waveform design method

The unipolar trapezoidal is the most basic driving waveform of piezoelectric inkjet printheads which has three key parameters i.e. the time of voltage rising section t_{rise}, the time of voltage dwelling section $t_{dwell,}$ and the time of voltage falling section t_{fall} (Fig. 4). In this paper,