Model-based Adjustment of Droplet Characteristic for 3D Electronic Printing

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Abstract. The major challenge in 3D electronic printing is the print resolution and accuracy. In this paper, a typical mode - lumped element modeling method (LEM) - is adopted to simulate the droplet jetting characteristic. This modeling method can quickly get the droplet velocity and volume with a high accuracy. Experimental results show that LEM has a simpler structure with the sufficient simulation and prediction accuracy.

Keywords. Model-based adjustment, Droplet characteristic, 3D electronic printing

1 Introduction

3D electronic printing has been widely applied on manufacturing the low-cost electronic products, such as flexible electronics, radio frequency identification (RFID) tags, solar cells, organic light emitting diode (OLED) flexible packaging electronic devices, such as medical equipment [1]. A classical implementation for 3D electronic printing is to use drop-on-demand (DoD) piezoelectric (PZT) inkjet printhead to deposits conductive, dielectric, and non-conductive ink onto various substrates [2].

A typical DoD piezoelectric inkjet printhead for 3D electronic printing comprises a number of ink channels that are arranged in parallel [3]. A piezoelectric actuator covers all ink channels, which can generate pressure oscillations inside the ink channel to push the ink droplet out of the nozzle. Nowadays the developments of DoD printing are moving towards higher productivity and quality. Therefore, the adjustable small droplet sizes fired at high jetting frequencies must be implemented.

The printing quality of DoD piezoelectric inkjet printhead is reflected in many respects, such as the jetting direction, the droplet velocity, the droplet volume and so on. In practice applications, to meet the various requirements of 3D electronic printing and get a higher inkjet performance, the droplet characteristics of the ink have to be tightly controlled. For improving the droplet jetting performance, several operational issues, such as the residual vibrations and cross talk, should be taken a care.

To solve such problem, researchers have proposed many methods. One of most typical methods is using numerical techniques to model the DoD piezoelectric inkjet printhead [4], which focuses on the liquid filament volition of droplet

formation process with known pressure input boundary conditions after solving the nonlinear Navier-Stokes equations. This method provides directly visualized information about the acoustic pressure wave travelling inside the channel [5]. Another typical method is using analytical modeling method with a higher simulation speed. This method can describe the ink channel dynamics, although the accuracy of analytical models is lower than numerical models. Based on several assumptions and simplifications, analytical models can provide a simple and timesaving way to model-based control droplet generator with a sufficient accuracy [6].

In this work, we adopted a typical analytical model - lumped element modeling method - to simulate the droplet formation process. The advantage of this method is its simpler structure with the sufficient simulation accuracy. After setting a series of desired droplet characteristics, a grid search method is applied to determine the parameters of printhead driving waveform.

The rest of this paper is organized as follows: In Section 2, a review of original lumped element modeling droplet generator is present. The simulation results of droplet volume and velocity decide the most suitable model in Section 3. The prediction process of droplet characteristics is built in Section 4. Finally, concluding remarks are collected in Section 5.

2 Lumped Element Modeling

A classical LEM is given to simulate jetting characteristics of PZT printhead, as shown in Figure 1. The equivalent circuit model is constructed by the energy storage elements and ideal dissipative terminal. In this electroacoustic system, pressure and voltage are independent variables, while current and volumetric flow rate are dependent variables. Model structure shows that the energy converts from electrical energy to mechanical energy, then to fluidic/acoustic energy, and finally to kinetic energy, as described in Figure 1(b). The droplet generator structure can be characterized by equivalent acoustic mass (representing stored kinetic energy) and acoustic compliance (representing stored potential energy), in which the corresponding equivalent circuit models are supported by various fluid mechanisms, as represented in Fig. 1(a) and 1(c). Furthermore, the piezo-ceramic model is constructed based on the electro-fluidic/acoustic theory [7]. The neck model is built on the velocity profile function [8]. The nozzle model is constructed according to the end correction for an open tube theory [9].

Fig.1. Schematic overview of lumped-element modeling for PZT printhead.

(a) Droplet generator structure (b) Model structure (c) Equivalent circuit model

As the equivalent circuit model shown in Figure 1, excitation voltage V_{ac} is applied to piezoelectric ceramic to create mechanical deformation. Coupling coefficient ϕ_a represents a conversion from mechanical domain to acoustic domain. C_{eb} is the blocked electrical capacitance of the piezoelectric material. In the acoustic domain, C_{ad} and C_{ac} represent the acoustic compliance of piezo-ceramic and channel. R_{ad} , R_{aN} , and R_{aO} are the acoustic resistance due to structural damping, neck tapering, and fluid flowing out of nozzle, respectively. M_{ad} , M_{aN} , and M_{aRad} represent the acoustic mass of piezoceramic, neck, and nozzle in proper order, respectively.

The dimensions of droplet generator and physical properties of nano-silver ink provided by the LEED-PV Corporation are listed in Table 1, and calculation formulas of LEM model parameters are provided in Eq. 1 -9.

Table 1. Droplet generator parameters

	Parameter	Unit	Value
Printhead	Channel volume, V_0	pL	166000
	Channel length, L_0	um	7200
	Nozzle radius, a_0	um	13.5
	Neck length, L	um	45
	Piezoceramic thickness, h	um	25
	Free electrical capacitance, C_{eF}	nF	2.8
Ink	Free electrical capacitance, σ	N/m	45×10^{-3}
	Viscosity, μ	$Kg/(m*s)$	15
	Density, ρ_0	Kg/m^3	1.05×10^3
	Sonic speed, C_0	m/s	1400

$$R_{aN} = (2 + \frac{a_0}{r}) \frac{\sqrt{2\mu\rho_0\omega}}{\pi r^2} \quad (1)$$

$$M_{aN} = \frac{\rho_0(t + \Delta t)}{\pi r^2} \quad (2)$$

$$\Delta t = 0.85r(1 - 0.7\frac{r}{a_0}) + 0.85r \quad (3)$$

$$C_{ad} = \frac{\pi r^6(1 - \nu^2)}{16Eh^3} \quad (4)$$

$$M_{ad} = 4\rho_0L / 3\pi a_0^2 \quad (5)$$

$$R_{aD} = 2\xi\sqrt{(M_{ad} + M_{aRad}) / C_{ad}} \quad (6)$$

$$C_{eB} = C_{eF}(1 - \kappa^2) \quad (7)$$

$$R_{aO} = \frac{\rho_0 c_0}{\pi r^2} [1 - \frac{2J_1(2kr)}{2kr}] \quad (8)$$

$$M_{aRad} = 8\rho_0 / 3\pi^2 a_0 \quad (9)$$

where u is viscosity, w is wave frequency, and a_0/r is gradients ratio, V_0 is volume of the cavity, E is the elastic modulus, ν is Poisson's ratio, and h is the thickness, ξ is the experimentally determined damping factor [8], J_1 is the Bessel function of the first kind, and $k = w/c_0$, κ^2 is electroacoustic oupling factor.

3 Simulation

For industry applications in printable electronics fabrication, the printhead must work at a certain status to meet many restrictive conditions. Among them, the most important problem is choosing the appropriate combinations of the driving waveform parameters for the used conductive inks. However, an exhausting manual selective process inevitably wastes a lot of time. Therefore, the computer-aided methods are urgently needed for searching these appropriate combinations efficiently and robustly.

Fig.2. Predictive droplet volume and velocity with different with various dwell time $T_2=2*T_1$

(a) Simulation curves of outflow change (b) Simulation curves of droplet average velocity

As mentioned above, the LEM model is chosen to simulate jetting characteristics for the nano-silver ink. Here, an illustrative example is given to display the effect of predicting the typical combinations of waveform parameters with different dwell times ($T_1 = 3\sim8\mu s$, $T_2 = 2*T_1$) and the same amplitude (12V). The properties of nano-silver ink provided by the LEED-PV Corporation have been listed in Table 1. In Figure 2, the predicted outflow and average velocity curves with various dwell times are depicted. We can observe from Fig. 2(a) that, before the droplets rush out of the nozzle, the depth of the inhaled meniscus is proportional to dwell time. From Figure 2(b), the time of the droplet appearing is postponed with the increase of dwell time. That is, both two simulation phenomena consist with the theoretical analysis results in [10].

Table 2. Predictive droplet volume (pL) and velocity (m/s)

$T_2 \backslash T_1$	7	7.5	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
7												
7.5												
8.5												
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9.5												
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10.5												
11												
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4	V	11.9	12.7	14.3	14.6	14.9	15.1	15	14.	14.	Defaul	Defaul	Defaul
	S	3.95	4.17	4.78	4.91	5.00	4.89	4.7	4.5	4.3	Defaul	Defaul	Defaul
4. 5	V	11.7	12.5	15	15.5	15.9	16.2	16	15.	15.	14.7	13.9	Defaul
	S	4.21	4.51	5.16	5.32	5.48	5.60	5.4	5.2	5.0	4.82	4.66	Defaul
5	V	Defaul	Defaul	15.1	15.7	16.3	16.7	16.	16.	16.	15.7	15	14.2
	S	Defaul	Defaul	5.31	5.53	5.72	5.87	6.0	5.8	5.6	5.40	5.25	5.09
5. 5	V	Defaul	Defaul	15.1	15.9	16.5	16.8	16.	17.	16.	16.5	16	15.4
	S	Defaul	Defaul	5.24	5.50	5.72	5.93	6.0	6.2	6.0	5.71	5.51	5.37
6	V	Defaul	Defaul	Defaul	Defaul	15.8	16.3	16.	16.	16.	16.5	15.8	14.95
	S	Defaul	Defaul	Defaul	Defaul	4.95	5.15	5.3	5.4	5.6	5.44	5.19	4.94
6. 5	V	Defaul	Defaul	Defaul	Defaul	Defaul	Defaul	15.	15.	16	15.5	15.0	14.3
	S	Defaul	Defaul	Defaul	Defaul	Defaul	Defaul	4.7	4.8	4.9	5.03	4.90	4.69

Fig. 3. A sequence of pictures of droplet falling from nozzle

4 Prediction

In this experiment, an illustrative example under desired conditions is presented to demonstrate the feasibility and effectiveness of the proposed method for predicting jetting characteristics. The dimensions of droplet generatorand

properties of the nano-silver ink are listed in Table 1. In order to reach a high printing resolution and good quality of droplet impact with the substrate, the desired conditions involve that the droplet volume is smaller than 14pL and the droplet velocity is larger than 5 m/s.

Based on the prediction procedure, the predictive values of drop volume/velocity with various dwell times T_1 and T_2 are listed in Table 2. According to the desired conditions, two combinations of parameters are found out: $T_1 = 5\mu\text{s}/T_2 = 13\mu\text{s}$, and $T_1 = 5\mu\text{s}/T_2 = 7.5\sim 8\mu\text{s}$. After a small range search around predictive values in the actual test, the combination of $T_1 = 4.9\mu\text{s}/T_2 = 7.7\mu\text{s}$ is finally chosen. The dynamic effect of jetting characteristics driven by this combination is shown in Figure 2. From this figure, the jetting characteristics satisfy the specified desired conditions quite well. Meanwhile, almost no satellite droplet emerges after jetting the main droplet.

5 Conclusion

The lumped element modeling based on linear model of piezoelectric ceramic has been successfully used to simulate piezo-electric droplet generator for 3D electronic printing. In this work, the droplet volume/velocity curves simulated can carry sufficient information to distinguish nanosilver droplet formation process. LEM model is also successful in predicting jetting characteristics under desired conditions.

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