*Bulgarian Chemical Communications, Volume 49, Number 1, (pp. 193 – 198) 2017*

# Droplet characteristic adjustment method based on LEM for 3D electronic printing

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Received February 20, 2016; Revised August 30, 2016

The major challenge in 3D electronic printing is the print resolution and accuracy. In this paper, a typical mode - lumped element modeling (LEM) method - 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 sufficient simulation and prediction accuracy.

**Keywords:** Droplet characteristic adjustment, Lumped element modeling, 3D electronic printing

## INTRODUCTION

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

A typical DoD piezoelectric inkjet print head for 3D electronic printing is comprised of a number of ink channels that are arranged in parallel [3]. A piezoelectric actuator covers all the ink channels that 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 a DoD piezoelectric inkjet print head is reflected in many respects, such as the jetting direction, the droplet velocity and the droplet volume. The practical applications meeting the various requirements of 3D electronic printing require a higher inkjet performance, while the droplet characteristics of the ink have to be tightly controlled. To improve the droplet jetting performance, several operational issues, such as the residual vibrations and cross talk, should be considered.

To solve such a problem, the researchers have proposed many methods. One of the most typical methods is using numerical techniques to model the DoD piezoelectric inkjet print head [4], which focuses on the liquid filament evolution of the 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 the analytical modeling method with a higher simulation speed. This method can describe the ink channel dynamics, although the accuracy of the analytical models is lower than that of the numerical models. Based on several assumptions and simplifications, the analytical models can provide a simple and time saving way to control via modeling the droplet generator with sufficient accuracy [6].

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

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

## LUMPED ELEMENT MODELING

A classical LEM is presented to simulate the jetting characteristics of a PZT print head, as shown in Fig. 1. An equivalent circuit model is constructed with the aid of the energy storage elements and the ideal dissipative terminal. In this electro-acoustic system, the pressure and voltage are independent variables, while the current and volumetric flow rate

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are dependent variables. The model structure shows that the energy converts from electrical energy to mechanical energy then to fluid/acoustic energy and finally into kinetic energy as described in Fig. 1(b). The droplet generator structure can be characterized by equivalent acoustic mass (representing the stored kinetic energy) and acoustic compliance (representing the 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 electric fluid/acoustic theory [7]. The neck model is built on the velocity profile function [8]. The nozzle model is constructed in accordance with the end correction for an open tube theory [9]

The equivalent circuit model is shown in Figure 1 the excitation voltage $V_{ac}$ is applied to a piezoelectric ceramic to create mechanical deformation.

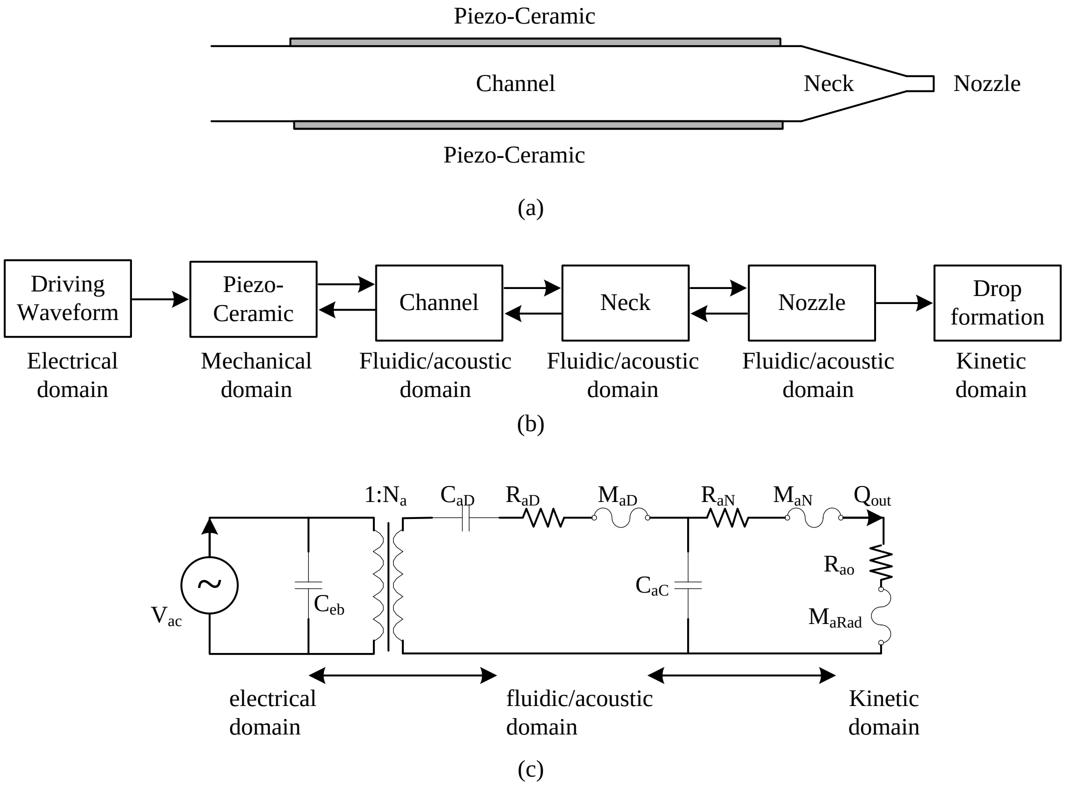


**Fig.1.** Schematic overview of lumped-element modeling for a PZT print head: (a) Droplet generator structure (b) Model structure (c) Equivalent circuit model.

**Table 1.** Droplet generator parameters.

| | Parameter | Unit | Value |
|---|---|---|---|
| Print head | 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, $\sigma$ | *N/m* | $45*10^{-3}$ |
| | Viscosity,$u$ | *Kg/(m*s)* | 15 |
| | Density, $\rho_0$ | *Kg/m*$^3$ | $1.05*10^3$ |
| | Sonic speed, $C_0$ | *m/s* | 1400 |

The coupling coefficient $\phi_a$ represents a conversion from the mechanical domain to the 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 the piezoceramic and channel. $R_{aD}$, $R_{aN}$ and $R_{aO}$ are the acoustic resistance due to structural damping, neck tapering and fluid flowing out of the nozzle, respectively. $M_{aD}$, $M_{aN}$ and $M_{aRad}$ represent the acoustic mass of the piezoceramic neck and nozzle in the proper order, respectively.

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

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

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

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

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

$$M_{aD} = 4\rho_0 L / 3\pi a_0^2 \quad (5)$$

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

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

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

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

where $u$ is viscosity, $w$ is the wave frequency and $a_0/r$ is the gradients ratio, $V_0$ is the volume of the cavity, $E$ is the elastic modulus, $v$ is Poisson's ratio and $h$ is the thickness, $\xi$ is the experimentally determined damping factor [18], $J_1$ is the Bessel function of the first kind and $k = w/c_0$, $\kappa^2$ is the electro-acoustic coupling factor.

## SIMULATION

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

As mentioned above, the LEM model is chosen to simulate the jetting characteristics of the nanosilver ink. Here, an illustrative example is given to display the effect of predicting the typical combinations of waveform parameters with different dwell times ($T_1$ = 3~8μs, $T_2 = 2*T_1$) and the same amplitude (12V). The properties of the nanosilver ink provided by the LEED-PV Corporation have been listed in Table 1. In Fig. 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 the dwell time. From Fig. 2(b), the time of the droplet appearing is postponed with the increase of the dwell time. That is, both simulation phenomena consist of a theoretical analysis of the results in [10].

## PREDICTION

In this experiment, an illustrative example under the desired conditions is presented to demonstrate the feasibility and effectiveness of the proposed method for predicting the jetting characteristics. The dimensions of the droplet generator and the properties of nanosilver 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 require that the droplet volume is smaller than 14 pL and the droplet velocity is larger than 5 m/s.

Based on the prediction procedure, the predictive values of the 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 the parameters are found: $T_1$ = 5μs/$T_2$ = 13μs and $T_1$ = 5μs/$T_2$ = 7.5~8 μs. After a small range search around the predictive values in the actual test, the combination of $T_1$ =4.9 μs/$T_2$ = 7.7 μs is finally chosen. The dynamic effect of the jetting characteristics driven by this combination is shown in Figure 2. From this figure, it is clear that the jetting characteristics satisfy the specified desired conditions quite well. Meanwhile, almost no satellite droplets emerge after jetting the main droplets.

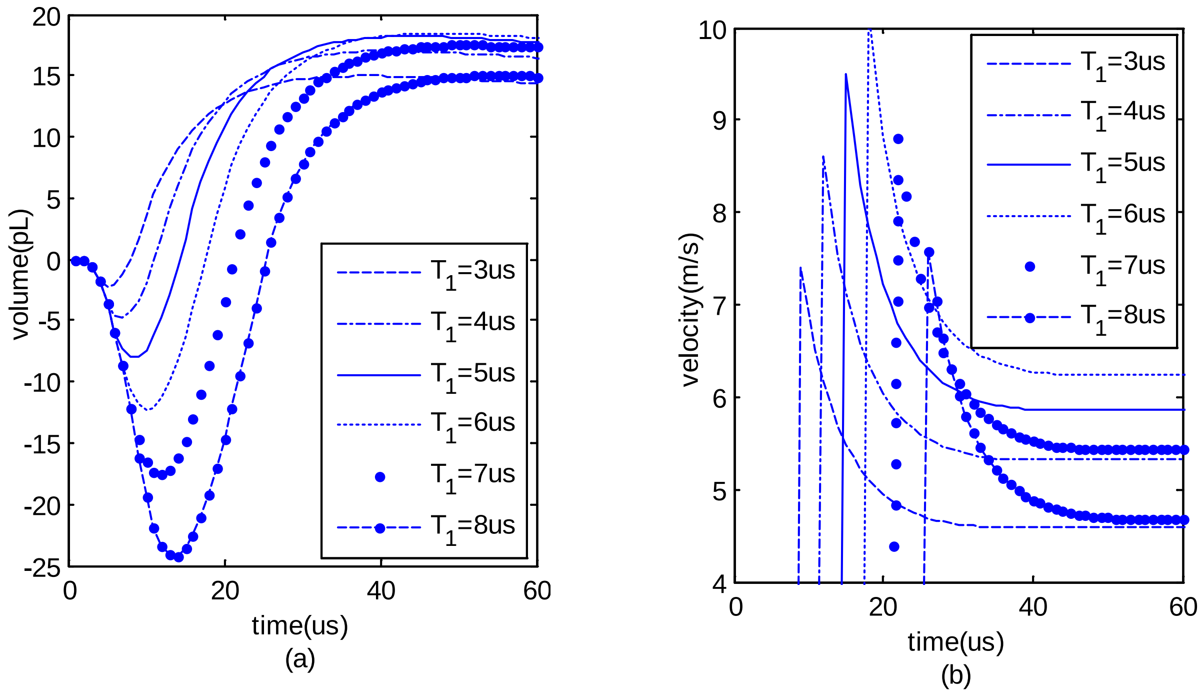


**Fig.2.** Predictive droplet volume and velocity with a different dwell time $T_2$=2*$T_1$
(a) Simulation curves of the outflow change (b) Simulation curves of the droplet average velocity

**Table 2.** The predictive droplet volume (*pL*) and velocity (*m/s*)

| $T_1$ \ $T_2$ | | 7 | 7.5 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 | 11.5 | 12 | 12.5 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | V | 11.9 | 12.7 | 14.3 | 14.6 | 14.9 | 15.1 | 15 | 14.7 | 14.2 | Default | Default | Default |
| | S | 3.95 | 4.17 | 4.78 | 4.91 | 5.00 | 4.89 | 4.71 | 4.51 | 4.35 | Default | Default | Default |
| 4.5 | V | 11.7 | 12.5 | 15 | 15.5 | 15.9 | 16.2 | 16 | 15.7 | 15.3 | 14.7 | 13.9 | Default |
| | S | 4.21 | 4.51 | 5.16 | 5.32 | 5.48 | 5.60 | 5.43 | 5.23 | 5.01 | 4.82 | 4.66 | Default |
| 5 | V | Default | Default | 15.1 | 15.7 | 16.3 | 16.7 | 16.8 | 16.6 | 16.3 | 15.7 | 15 | 14.2 |
| | S | Default | Default | 5.31 | 5.53 | 5.72 | 5.87 | 6.00 | 5.83 | 5.63 | 5.40 | 5.25 | 5.09 |
| 5.5 | V | Default | Default | 15.1 | 15.9 | 16.5 | 16.8 | 16.9 | 17.1 | 16.9 | 16.5 | 16 | 15.4 |
| | S | Default | Default | 5.24 | 5.50 | 5.72 | 5.93 | 6.09 | 6.24 | 6.01 | 5.71 | 5.51 | 5.37 |
| 6 | V | Default | Default | Default | Default | 15.8 | 16.3 | 16.4 | 16.5 | 16.5 | 16.5 | 15.8 | 14.95 |
| | S | Default | Default | Default | Default | 4.95 | 5.15 | 5.33 | 5.49 | 5.64 | 5.44 | 5.19 | 4.94 |
| 6.5 | V | Default | Default | Default | Default | Default | Default | 15.5 | 15.9 | 16 | 15.5 | 15.0 | 14.3 |
| | S | Default | Default | Default | Default | Default | Default | 4.73 | 4.85 | 4.95 | 5.03 | 4.90 | 4.69 |

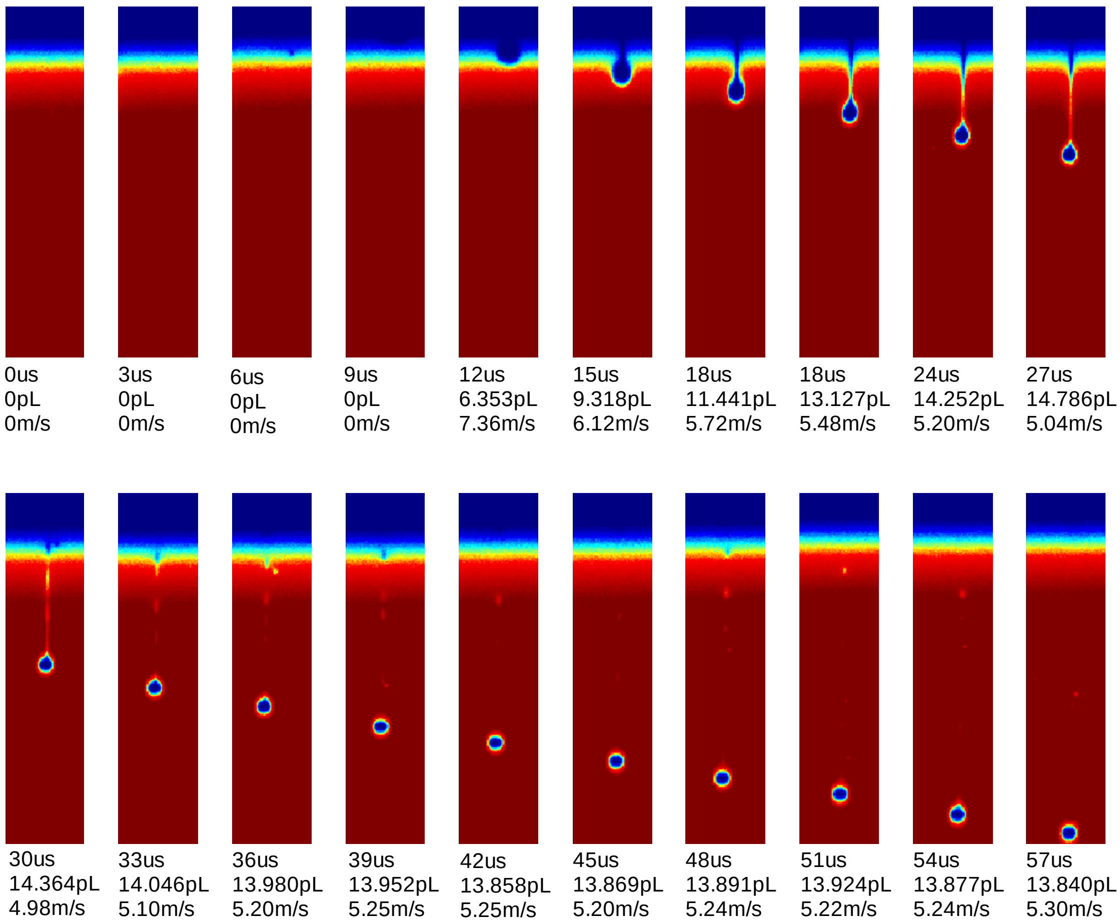


**Fig 3.** A sequence of pictures of a droplet falling from the nozzle.

## CONCLUSION

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

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# МЕТОД ЗА НАСТРОЙКА НА РАЗМЕРА НА КАПКИТЕ ПО LEM-МЕТОДА ЗА 3D ЕЛЕКТРОННО ПЕЧАТАНЕ

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Постъпила на 20 февруари, 2016 г.; коригирана на 20 август, 2016 г.

(Резюме)

Главното предизвикателство при 3D-електронното печатане са разделителната способност и прецизността. В настоящата работа е приложен метода LEM (lumped element modeling) за да се симулират характеристиките на капките и струите от мастило. Този метод дава бързо и с голяма точност скоростта на капките и обема им. Експериментите показват, че LEM-методът има проста структура с достатъчна точност на симулирането и предвижданията.