Modeling and Optimizing Industrial Inkjet Printhead for Printable Electronics Fabrication

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Abstract. The most significant issues in printable electronics fabrication are the printing quality and efficiency delivered by drop-on-demand (DOD) industrial inkjet printhead. Aiming to characterize the nonlinear behaviors of piezoelectric inkjet printhead, the dynamic lumped element model (DLEM) is proposed to cast the original LEM into a time-varying and nonlinear fashion. At the same time, the PSO-based optimization for parameters is incorporated in DLEM. Due to new characteristics, DLEM can accurately simulate the inkjet-printed nano-silver droplet formation process and effectively predicate optimal combinations of high-frequency driving waveform with high printing quality. From extensive experimental studies, the effectiveness and efficiency of the proposed DLEM is validated.

Introduction

Recently, the novel printable electronics (PE) fabrication technology has been significantly developed to meet the essential need for automation, miniaturization, and the reduction of costs and environmental impact in various manufacturing applications\cite{1,2}. As the increasingly attractive alternative to construct PE application, the inkjet printing deposits various versatile nano-materials on flexible substrates in non-contact pattern\cite{3,4}. In each specific application case, the required performance in terms of velocity, volume, and positioning should be imposed on the involved inkjet printhead. Generally speaking, the properties of jetted droplet, i.e., the droplet viscosity and the droplet surface tension, play an important role in the print quality. In addition, the essential physical issues, such as residual vibrations and cross-talk, also influence the print performance of the PZT printhead. The lumped element modeling (LEM) technique has been proven as an effective way of predicting and controlling the complex droplet formation process in various experimental cases\cite{5-8}. However, when facing the new conditions such as asymmetry strain, this method cannot perform competently.

In order to address the concerning issues mentioned above, this paper extends the canonical LEM to the dynamic, non-linear fashion called dynamic LEM (DLEM), which emphasizes the nonlinear characteristic of PZT printhead. At the same time, to obtain the optimal driving waveform parameters for DLEM, the optimization scheme based on the particle swarm optimization (PSO) algorithm is constructed. In the experiment, we validate the models and show the significant merit of the PSO-based optimization scheme.
Dynamic lumped element modeling (DLEM)

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

The original LEM model was firstly proposed by Gallas to simulate the working process of PZT printhead [8], as shown in Fig.1. Fig.1(a) represents the physical structure of the piezo-ceramic model. Fig.1(b) describes the complex energy transformation from electrical energy, mechanical energy, to kinetic energy, characterized by equivalent acoustic mass and acoustic compliance. The abstracted equivalent circuit model derived from fluid mechanisms comprises of the energy storage elements and ideal dissipative terminal.

As shown in Fig.(b), in the electrical domain, parameter $V_{ac}$ is used to drive the mechanical deformation, while $C_{eb}$ represents the piezoelectric blocked capacitance. In the fluidic/acoustic domain, the static acoustic compliances of $C_{aD}$ and $C_{aC}$ are used to combine the piezo-ceramic with chamber. $R_{aD}$, $R_{aN}$ and $R_{aO}$ represent the acoustic resistance due to structural damping, neck tapering and fluid flowing out of nozzle, respectively. In the kinetic domain, $M_{aD}$, $M_{aN}$ and $M_{aRad}$ are static acoustic mass parameters corresponding to piezo-ceramic, neck and nozzle in proper order.

Fig. 2: Equivalent electrical circuit model with dynamic coefficients.
In order to characterize the piezo-ceramic dynamic response in time-domain, the improved equivalent electrical circuit model with dynamic coefficients is given as shown in Fig.2. The corresponding resistance and capacitance can be defined as Eq.(1), where \( P_1 \), \( P_2 \), \( M_1 \) and \( M_2 \) are adjusting coefficients.

\[
\begin{align*}
C_2 &= p_1 I^2 \\
C_2 &= p_2 I^2 \\
R_2 &= m_1 I^2 \\
R_3 &= m_2 I^2 \\
C(I) &= C_1 (1 + R_1 I^2 + P_2 I^4) \\
R(I) &= R_1 (1 + M_1 I^2 + M_2 I^4)
\end{align*}
\]

(1)
Particle swarm optimization

Particle swarm optimization (PSO) is a classical swarm intelligence algorithm [9], where each particle adjusts its position to search the global optimum according to its own experience and that of its neighbors. Each particle is $x_i = (x_{i1}, x_{i2}, ..., x_{iD})$ and its historical best position is $P_i = (P_{i1}, P_{i2}, ..., P_{iD})$, and the best position of the population is $p_g$. In each generation $t$, the particles are manipulated according to the following equations:

$$a_i = c_1 r_1 (p_i - x_i) + c_2 r_2 (p_g - x_i) \quad (2)$$

$$v_i = \chi (v_i + a_i) \quad (3)$$

$$x_i = x_i + v_i \quad (4)$$

where $c_1$ and $c_2$ are two learning rates that control respectively the proportion of social transmission and individual learning in the swarm and $r_1, r_2$ are two random vectors uniformly distributed in [0, 1]. $\chi$ is known as the constriction coefficient.

Experimental setup

As shown Fig.3, in the experiment scheme, the CCD camera with a cold source of halogens aims to capture the droplet formation and evaluate the volume, velocity of droplet and the profile of meniscus. The visualization system consists of a cold source of halogens (XAO LG150) and a CCD camera. The adjusted driving waveform is generated by arbitrary wave generator (RIGO DG2014A). Ink supply unit is used to guarantee the suitable negative force needed in the inkjet printing system.

Simulation results

Fig.4 illustrates the droplet volume (diameter) formation process under different LEM model. From Fig 4, there is no obvious between the simulation and the measured results, from which, we can obtain the similar conclusion that the proposed DLEM model endowed with PSO optimization operation can significantly improve the simulation accuracy on the droplet formation process. The dynamic effect of jetting characteristics driven by DLEM is shown in Fig.5. From this figure, the jetting characteristics satisfy the specified restrictive conditions quite well.

Summary

Aiming to address the concerning issues of adopting inkjet technology into the PE domain, this paper casts the original LEM into dynamic LEM (DLEM). In the proposed DLEM, the equivalent circuits are modified with the nonlinear time-varying capacitance, inductance and resistor in series. At the same time, the PSO-based parameters optimization is incorporated in DLEM. From the experimental results, the proposed DLEM has significant merits of simpler structure, sufficient simulation and predictive accuracy.
References

[1] M. Singh, H.M. Haverinen, P. Dhagat, G.E. Jabbour. Inkjet printing: process and its applications. Advanced Materials, Vol. 22, 2010, pp. 673–685.

[2] H. Jaehyung, W. Alan, K. Antoine, Energetics of metal–organic interfaces: New experiments and assessment of the field, Materials Science and Engineering: R: Reports, Vol. 64, 2009, pp. 1–31.

[3] J.K. Byung, J.H. Je, Geometrical characterization of inkjet-printed conductive lines of nanosilver suspensions on a polymer substrate, Thin Solid Films, Vol. 518, 2010, pp. 2890–2896.

[4] A.A. Khalate, Optimization-based feedforward control for a Drop-on-Demand inkjet printhead, American Control Conference (ACC), 2010, pp. 2182–2187.

[5] H. Seitz, J. Heinzl, Modeling of a Microfluidic Device with Piezoelectric Actuators, Journal of Micromechanics and Microengineering, Vol. 14, 2004, pp. 1140–1147.

[6] S. Kim, J. Sung, M. H. Lee, Pressure Wave and Fluid Velocity in a Bend-Mode Inkjet Nozzle with DoublePZT Actuators, Journal of Thermal Science, Vol. 22, No. 1, 2013, pp. 29–35.

[7] G. Wassink, Inkjet printhead performance enhancement by feedforward input design based on two-port modeling, Ph. D. thesis, Delft University of Technology, 2007.

[8] Q. Gallas, R. Holman, T. Nishida, B. Carroll, M. Sheplak and L. Cattafesta, Lumped Element Modeling of Piezoelectric-Driven Synthetic Jet Actuators, AIAA Journal, Vol. 41, No. 2, 2003, pp. 240–247.

[9] J. Kennedy, R. C. Eberhart, Particle swarm optimization, In: Proceedings of the 1995 IEEE International Conference on Neural Networks, vol. 4, 1995, pp. 1942-1948.