Design, modeling, and performance analysis of a new dispensing system based on compliant mechanism

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Abstract
Jet dispenser is widely used in microelectronic packaging, semiconductor industry, life science, and rapid manufacturing fields. As the requirement for dispensing accuracy and speed become higher and higher, especially for viscous materials, the traditional mechanisms cannot meet the high precision dispensing. This paper presents a new jetting dispenser using the compliant mechanism with amplifier components to design the dispenser, which gain the motion and force from the elastic deformation of flexible hinges. To describe the mechanical property of the jetting dispenser, the model of the jetting dispenser was built by employing a pseudo-rigid-body method. To predict accurately droplet volume, we established the model by describing the forming process of droplet. Furthermore, the errors of the droplet volume were analyzed based on the model. The prototype of the dispenser was built and the effects of driving voltage, radius of spray chamber, glue supply pressure, glue viscosity, and turn-on time of hammer on the droplet were analyzed experimentally. The analytical results are in good agreement with experimental results, which the advantages of the presented jetting dispenser with a new design concept are validated. This research provided a new idea and modeling method for the future application of the dispensing system.

Keywords
Micro-injection dispensing system, compliant mechanism, error analysis, prediction model, modeling

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Introduction

In recent years, a dispensing system has been widely used in many applications such as microelectronic packaging, semiconductor industry, life science, and rapid manufacturing fields. In these fields, the requirement for dispensing accuracy and speed becomes higher and higher, especially for viscous materials.

So far, numerous types of dispensing system have been developed and successfully implemented in these applications. There are classified into two types: contact-based dispenser and non-contact dispensing technique. Using contact-based dispensing method, the droplets with high accuracy need the distance between the needle and the substrate to the same, in which the dispenser nozzle is required to contact with a substrate via dispensed adhesive. Maintaining such a consistent dispensing gap requires contact with the substrate, increases the cycle time, and complicates the process. Thus, the dispensing system has been presented as a non-contact jetting method. Essentially, the dispensing method use a closed-loop, positive shut-off piston to dispense adhesive. The fluid is pressurized at the syringe to ensure a constant flow of material throughout the fluid path of the dispenser. Despite these benefits, the increasing requirements for micro-volumes of high viscosity fluids at a high flow rate need an advanced dispensing system to be presented. Furthermore, the predication of droplet volume as dispensing high viscosity fluids is also important issuers to be resolved.

The piezostack-driven jetting dispenser utilizing a striking needle to dispense fluids has the high driving force and non-contact dispensing characteristics, and it can be used in many high-viscosity liquid dispensing applications to obtain a series of droplets with small volumes. When a voltage is applied to the piezostack, the output displacement from the piezoelectric actuator (PZT) is transmitted to the colliding needle through different transmission methods, including mainly hydraulic and leverage. Khan and Nguyen designed an injection dispensing system by combining traditional lever mechanism with hydraulic amplifier components. However, the lever mechanism has a fast response but a small pin stroke, which is difficult to meet the high-viscosity fluid. In addition, the friction between components of the mechanism during dispensing process shows that the dispensing accuracy is not high. Using the way hydraulic pressure drives the needle, the consistency of droplets is poor due to the increase in the temperature of the glue in the spray chamber. The compliant mechanism is different from general rigid mechanisms that transfer force and displacement by applying the deflection of its flexible members, in which it has many advantages such as no friction, no clearance, and high precision. Therefore, these properties of compliant mechanism are suitable for designing the micro-injection dispensing system with high precision and fast response.

At present, the method of jetting dispenser has the disadvantage such as stickiness of droplets and satellite droplets, and the consistency is poor. To solve the above issues, it is necessary to analyze the forming process of the droplets.
Neguyen et al.\textsuperscript{14} established the unsteady laminar flow model for the stability of injection dispensing system, but the computational process of this method is complex. Lu et al.\textsuperscript{17} established the bond-graph model for the jetting dispenser by integrating the electromechanical model with the fluid model. This method is simple and applicable, but the precision of the model is low. Furthermore, the effect of the temperature on the consistency of the droplets from the dispensing system is not considered, and a further study should be made to improve the predictive model for estimating the droplet size.

The rest of the article is organized as follows. Section “Design of dispensing system” proposes the design of a jetting dispenser based on compliant mechanism. The volume prediction model for the droplets size is deduced in section “Prediction model of droplet size.” The performance and error analysis are carried out in section “Performance and error analysis,” in which the accuracy of the jetting dispenser is discussed. A compensation method for describing the errors of the droplet volume caused by the temperature increase in the long-time jetting process is proposed. Section “Conclusion” concludes this article.

**Design of dispensing system**

The micro-injection dispensing system in Figure 1(a) is composed of firing pin valve, syringe (glue supply device), and drive device. The syringe is connected with the glue inlet of the valve to supply the glue for the dispensing machine. The driving device is equipped with the colliding pin to drive it to move up and down. The working principle of the system shown in Figure 1(b) is as follows: the continuous upward and downward movement of the needle makes the nozzle in the state of opening-closing-opening circulation, which the nozzle cuts off fluent into a series of droplets and accomplishes the continuous dispensing operation. It is key issue to design a driving part with desired stroke and actuation force. Therefore, we adopt a piezostack-driven compliant mechanism which can move the needle up and down by using its elastic deformation, which pushes the adhesive glue out of the nozzle.

As is well known, the piezostack actuator can offer large force, fast response, and high operating frequency. However, the primary limitation of the piezostack actuator is its small strain. To dispense adhesive fluid, a magnification mechanism should be employed to magnify the piezostack actuator displacement. In this study, a compliant mechanism with magnification is proposed. When a voltage is applied to the piezostack, it causes the displacement of the input end of the compliant mechanism, and the resulting displacement of the needle is magnified via the compliant mechanism. The design principle is shown in Figure 2(a); a leverage mechanism is employed to transfer the displacement at the input end and anticlockwise rotation of the pendulum rod causes the output end to move up and down. Using the design idea, the flexure-based compliant mechanism is designed as shown in Figure 2(b). The leverage is designed as the compliant mechanism with circular flexure hinge. To improve the accuracy of the mechanism, a symmetrical flexible
spring $E$ and $E'$ is used to convert the rotation of the pendulum rod into linear movement of the output end equipped with the needle. Meanwhile, flexible spring $E$ and $E'$ have the same structure parameters and the same stiffness, so that the couple spring can act as a linear guiding mechanism when they are symmetrically distributed. The driving device is fabricated by using a three-dimensional (3D) printer. The micro-spray dispensing prototype is shown in Figure 3. The glue supply device extrudes glue from the storage drum by using the high-pressure gas provided by the air compressor.

**Figure 1.** Composition and working principle of the micro-spray dispensing system: (a) composition and (b) working principle.

**Analytical model of dispensing system**

To obtain the analytical model on motion stroke, force, and dynamic response of the dispensing system, the pseudo-rigid-body method is used to establish the model
as follows. The flexure-based compliant mechanism is symmetrical from Figure 2, so the pseudo-rigid-body model can be described as Figure 4.

As shown in Figure 4, according to the level mechanism DCB, the displacement of the point B along axis $x$ can be expressed as

$$d_B = \left( \frac{l_2}{l_1} + 1 \right) d_i$$  \hspace{1cm} (1)

where $d_i$ is the input displacement of the actuator and $l_1$ and $l_2$ are the distance between point D and C, C and B, respectively.

**Figure 2.** Design of the compliant mechanism: (a) design principle and (b) structure and size.
Similarly, the output displacement can be obtained by the geometry relation of the structure BAE as follows

\[ d_o = l_4 \frac{d_B}{l_3} \]  

(2)

where \( l_3 \) and \( l_4 \) are the distance between point B and A, A and E, respectively. Thus, the displacement magnification of the compliant mechanism is

\[ \lambda = \left| \frac{d_o}{d_i} \right| = \frac{l_2 l_4 + l_1 l_4}{l_1 l_3} \]  

(3)

**Figure 3.** The prototype of micro-spray dispensing system.

**Figure 4.** Pseudo-rigid model of the compliant mechanism.
Next, the relationship between force and displacement is obtained by using the principle of virtual work. The virtual work produced by input and output force $F_i$ and $F_o$, respectively, is

$$
\delta W_i = F_i d_i \\
\delta W_o = F_o d_o
$$

(4)

The virtual work by flexure hinges can be expressed as

$$
\delta W_h = - \frac{1}{2} k_B \left[ (\delta \Theta_2)^2 + (\delta \Theta_1)^2 \right] - \frac{1}{2} k_A (\delta \Theta_3)^2
$$

(5)

where $k_A$ and $k_B$ are the stiffness of the flexure hinge A and B and $\delta \Theta_1$, $\delta \Theta_2$ and $\delta \Theta_3$ are virtual angular displacements of flexure hinges D, B and A, respectively, they can be expressed as

$$
\delta \Theta_1 = \frac{d_i}{l_1} ; \delta \Theta_2 = \frac{d_B}{l_1 + l_2} ; \delta \Theta_3 = \frac{d_B}{l_3}
$$

(6)

Combining equations (5)–(6), the virtual work $\delta W_h$ is

$$
\delta W_h = - \frac{1}{2} k_B \left[ \left( \frac{d_B}{l_1 + l_2} \right)^2 + \left( \frac{d_i}{l_1} \right)^2 \right] - \frac{1}{2} k_A \left( \frac{d_B}{l_3} \right)^2
$$

(7)

According to the principle of virtual work, the following expression can be obtained as

$$
\delta W = \delta W_i + \delta W_o + \delta W_h = 0
$$

(8)

$$
F_i d_i + F_o \left( \frac{l_2 l_4}{l_1 l_3} + \frac{l_4}{l_3} \right) d_i = \frac{1}{2} k_B \left[ \left( \frac{d_B}{l_1 + l_2} \right)^2 + \left( \frac{d_i}{l_1} \right)^2 \right] + \frac{1}{2} k_A \left( \frac{d_B}{l_3} \right)^2
$$

(9)

The driving force of piezoelectric actuator can be expressed as

$$
F_i = n k_p d_{33} V
$$

(10)

where $n$, $k_p$, and $d_{33}$ denote the stack number, stiffness, and piezoelectric strain coefficient of the PZT actuator, respectively, and $V$ is the voltage applied to the actuator. Substituting equation (10) into equation (9), the relationship between driving force and voltage can be obtained as follows

$$
F_o = \frac{k_B V}{1500 \lambda l_1^2} + \frac{k_A V}{3000 \lambda} \left( \frac{l_1 + l_2}{l_1 l_3} \right)^2 - \frac{n k_p d_{33} V}{\lambda}
$$

(11)
Prediction model of droplet size

The droplet size is determined by two processes including nozzle opening and closure. The glue flow rate during the two processes is analyzed as follows. The glue flow is shown in Figure 5 when the hammer goes up. The filling injection model is used to describe the glue flow. Assuming that the glue is a viscous incompressible fluid, the relationship between shear stress and rate is expressed by Newton’s viscous law

\[ \tau = -\mu \frac{du}{dr} \]  \hspace{1cm} (12)

where \( \tau \) and \( r \) are shear stress and radius and \( \mu \) and \( u \) are glue viscosity and flow velocity, respectively.

The cylindrical glue fluid unit with radius \( r \) and height \( dx \) is taken as analytical unit. Ignoring the influence of inertia force, the static equilibrium equation can be obtained as follows

\[ -\pi r^2 dp = 2\pi r \tau dx \]  \hspace{1cm} (13)
where \( dp \) is the pressure difference. Equation (13) can be rewritten as

\[
\frac{dp}{dx} = \frac{-2\tau}{r}
\]

(14)

Referring to literature,\(^{12}\) the relationship between the pressure difference \( dp \) and the unit height \( dx \) can be expressed as

\[
\frac{dp}{dx} = \frac{-\Delta p_1}{L_1}
\]

(15)

where \( L_1 \) is the height of main cavity and \( \Delta p_1 \) is the pressure difference of main cavity \( \Delta p_1 = p_i - p_c \).

Combining equations (12), (14), and (15), thus

\[
\frac{du}{dr} = \frac{-\Delta p_1 r}{2\mu L_1}
\]

(16)

Integrating equation (16), the flow velocity of glue in the main chamber can be obtained as

\[
u = -\frac{\Delta p_1 r^2}{4\mu L_1} + c
\]

(17)

where \( c \) is an integral constant. Using the boundary condition \( r = R, u = 0 \), \( c \) can be obtained

\[
c = -\frac{\Delta p_1 R^2}{4\mu L_1}
\]

(18)

where \( R \) is the radius of the main chamber. The glue velocity can be expressed as

\[
u = -\frac{\Delta p_1 (R^2 - r^2)}{4\mu L_1}
\]

(19)

From equation (19), the flow rate of the unit is

\[
dQ = udA = ud(\pi r^2) = 2\pi r u dr
\]

(20)

The glue flow in the dispensing chamber can be obtained by integral of equation (20)

\[
Q_1 = \frac{\pi(p_i - p_c)}{8\mu L_1}(R^4 - 2R^2 r_z^2 + r_z^4)
\]

(21)

where \( r_z \) is the radius of the needle.

Similarly, the flow in the ball-seat chamber is
\[ Q_2 = \frac{\pi(p_c - p_o)}{8\mu L_2} \left( 2R^2 r_p^2 - r_p^4 \right) \]  

(22)

where \( r_p \) and \( L_2 \) are the radius and height of the ball-seat chamber, respectively.

The unknown \( p_c \) can be obtained according to the relationship between \( Q_1 \) and \( Q_2 \)

\[ Q_1 - V_z = Q_2 \]  

(23)

where \( V_z \) is the volume change of the needle in the ball-seat chamber when the needle moves up and down, so it can be expressed as \( V_z = \pi r_z^2 v_z \). Combining equations (21)–(23), the \( p_c \) is as follows

\[ p_c = \frac{\pi p_i L_2 (R^4 - 2R^2 r_z^2 + r_z^4) - 8\mu L_1 L_2 \pi r_z^2 v_z}{\pi L_2 (R^4 - 2R^2 r_z^2 + r_z^4) + \pi L_1 (2R^2 r_p^2 - r_p^4)} \]  

(24)

Therefore, the flow \( Q_2 \) in the ball-seat chamber can be obtained by substituting equation (24) into (22).

The gel flow during the process when needle descends to shut the valve body is shown in Figure 6. The flow is formed by two channels, including backflow generated by pressure difference and downflow generated by hammer motion. The gel is

\[ \text{Figure 6. Schematic diagrams of glue flow when nozzle closure.} \]
regarded as a continuum and a fluid unit is analyzed. The momentum equation of the flow can be obtained using Navier–Stokes equation

\[ \rho \frac{du}{dt} + \frac{dp}{dx} = \frac{\partial}{\partial r} \left( r \frac{\partial \tau}{\partial r} \right) \]

(Subeq. 25)

Substituting equation (15) into equation (25), there is

\[ \rho \frac{du}{dt} = \frac{\Delta p_3}{L_1} \left( \frac{r_m^2}{r} - r \right) \]

(Subeq. 26)

where \( \Delta p_3 \) is the pressure difference in the main chamber \( \Delta p_3 = p_i - p_h \). The integral of equation (26) is

\[ \tau(r) = \frac{\Delta p_3}{2L_1} \left( \frac{r_m^2}{r} - r \right) \]

(Subeq. 27)

where \( r_m \) is the radius corresponding to the boundary between channel 1 and 2.

Substituting the boundary condition, \( r = R, u = 0, r = r_z \), and \( u = -v_z \), and equation (27) into equation (26), the velocity distribution of the glue is as follows

\[ u = \begin{cases} \int_{r_z}^{r} \frac{\Delta p_3}{2\mu L_1} \left( \frac{r_m^2}{r} - r \right) dr - v_z & \text{channel 1} \\ \int_{r}^{r_z} \frac{\Delta p_3}{2\mu L_1} \left( r - \frac{r_m^2}{r} \right) dr & \text{channel 2} \end{cases} \]

(Subeq. 28)

where \( v_z \) is the motion speed of the hammer. When \( r = r_m \), the flow velocities of channel 1 and 2 are equal, that is to say, there is

\[ \int_{r_z}^{r} \left( \frac{r_m^2}{r} - r \right) dr - \int_{r}^{r_m} \left( r - \frac{r_m^2}{r} \right) dr = v_z \frac{\Delta p_3}{2\mu L_1} \]

(Subeq. 29)

From equation (29), \( r_m \) can be written as

\[ r_m = \sqrt{\frac{v_z \Delta p_3 - \mu L_1 (2r_2^2 - R^2)}{\mu L_1 (3 \ln R - 4 \ln r_z - 1)}} \]

(Subeq. 30)

Substituting equation (30) into equation (28), the flow rate \( Q_3 \) of the gel in the main chamber can be obtained as follows

\[ Q_3 = \int_{r_z}^{R} 2\pi ru(r) dr = C_1 \frac{\pi (p_i - p_h)}{8\mu L_1} + C_2 \]

(Subeq. 31)

where \( C_1 = \left( R^4 - 2R^2r_m^2 - r_z^4 + 2R^2r_z^2 \right) \).
\[ C_2 = \pi R^2 v_z (r_z^2 - r_m^2) \]

Similarly, the flow rate of the gel in the spray chamber \( Q_4 \) is

\[ Q_4 = \frac{\pi (p_h - p_o)}{8 \mu L_2} \left( 2R^2 r_p^2 - r_p^4 \right) \]

Considering the gel is assumed to be incompressible and to behave as Newtonian fluids, the volume of the hammer is equal to the sum of the backflow and downflow volume

\[ Q_3 + Q_4 = V_z \]

Combining equations (31)–(33), \( p_h \) can be obtained as

\[ p_h = \frac{8 \mu L_1 L_2 \left[ \pi r_z^2 v_z - C_2 \right] - \pi p_i L_2 C_1}{\pi L_1 \left( 2R^2 r_p^2 - r_p^4 \right) - \pi L_2 C_1} \]

Substituting equation (34) into equation (32), the flow rate \( Q_4 \) can be acquired. Thus, the volume of the droplet is the integral of the flow rate of the gel in the spray chamber, and it can be obtained as follows

\[ V = \int_{0}^{t_1} Q_2 dt + \int_{0}^{t_2} Q_4 dt = t_1 Q_2 + t_2 Q_4 \]

where \( t_1 \) and \( t_2 \) are the time for the needle to rise and fall, respectively.

**Performance and error analysis**

**Experiment setup**

In this section, we carry out performance analysis of the proposed jetting dispenser. The experiment was set up as demonstrated in Figure 7, including jetting dispenser, PZT actuator, industry computer, and microscope. For experimental study, the developed jetting dispenser prototype is fabricated by 3D printer. Two PZT actuators (model: PST150, from Harbin CORE Tomorrow Science & Technology Corp.) are employed to drive the system. The microscope (model: 9XBPC, from bimu Corp.) is adopted to measure the volume of droplet. The microscope has imaging function and built-in software has the size-marking function to measure the diameter of the droplet. We think of the glue drops as spheres, and the volume of the drops can be calculated. The capacitive displacement sensor (model: PCI-6713, from NI Corp.) is used to measure the displacement of the impact pin, and the displacement signal is collected by A/D card through the signal conditioner. The dynamometer (model: ELK-200, from Elecall Corp.) is used to measure the driving force of the output end of the driving mechanism to the impact pin.
According to the working principle of the dispensing system describing in Figure 2, the dispensing droplet size and flow speed can be changed by the frequency and amplitude of the voltage employed to the PZT, and it is shown in Figure 8. To move up the needle, the voltage imposing on the first PZT is high level over a period time $t_1$, meanwhile another is the low level. By contrast, the voltage is contrast over a time period $t_2$ to realize needle moves down. The radius and length of the injection chamber are 0.15 and 6 mm, respectively. The radius and length of the main chamber are 5 and 15 mm. The radius of the needle is 1.5 mm. To gain the accurate volume of the droplet, we take a group of droplets measured by microscopy as test samples to calculate the average of these droplets.

**Performance analysis**

To test the driving force of the dispenser, the voltage range from 0 to 120 V is employed and the force corresponding to voltage can be measured by force sensor.
The relationship between the force and voltage is shown in Figure 9. It is observed that the maximum driving force is 95.4 N, and it is much larger than the resistance (3–9 N) of the needle generated when it rapidly moves. Thus, the driving force supplying from the dispenser can meet the requirement.

To obtain the motion stroke of the system, we apply the voltage (0–120 V) to measure the displacement of the needle, which the experiment results of the displacements are shown in Figure 10. The results show that the maximal displacement is 568 μm, and the results verified that the stroke designed for the needle is satisfied. Meanwhile, the needle displacement is 300 μm as the voltage is 60 V, and the corresponding driving force is 42.5 N. It can be concluded that the operating voltage range of dispensing system should be (60–120 V).

To investigate the influence of driving signal, the experiments with different voltage and frequency are carried out, and the results are shown in Figure 11. We can conclude the following from the results: (1) The voltage changed from 50 to 120 V in increments of 10 V, while the volume of droplets increase from 1.5 to 14.1 μL, illustrating that the higher the voltage, the larger the driving force and needle displacement, which it is more conducive to glue ejection. (2) The frequency changed from 0 to 300 Hz in increments of 50 Hz, and the volume of droplet decreases with the increase of one. When the frequency is more than 250 Hz, the droplet volume is close to zero because the nozzle reopens before it is fully closed, which leads to jet flow.

**Analysis of influencing factors for droplet volume**

From the volume estimation model, it can be observed that the volume of droplet is related to the radius of the injection chamber, the supply pressure, and viscosity of the glue. To evaluate the influence of these factors, the experiments were carried out in case of $r \in [0.15\text{–}0.75] \text{ mm}$, $P \in [0.2\text{–}1.2] \text{ mPa}$, $P \in [20\text{–}10^3] \text{ mPa s}$, $t_2 \in [5\text{–}30] \text{ ms}$, respectively.
The experimental and analytical results are shown in Figure 11(a)–(d). The following conclusions can be drawn from these results: (1) The volume of the droplet increases with the increase in the radius of the injection chamber. When the radius is more than 0.4 mm, the change in the volume is higher. (2) The droplet volume decreases as supply pressure increases, and it is approximated to a linear relationship. (3) The droplet volume increases from 3.1 to 11.2 when the opening time changes from 5 to 30 ms. (4) The analytical results are in good agreement with the experimental results, which shows the correctness of the deduced volume estimation model.

Error analysis

To illustrate the accuracy of the model, 10 groups of experiments are conducted under the same conditions. Twenty droplets is injected in each group in case the sampling interval between each group is 3 and 5 min, respectively. The theoretical and experimental results corresponding to each group are shown in Figure 12(a) and (b). From the figure, the volume estimation model can predict the droplet volume well, but the error increases with the injection time. By comparing Figure 12(a) and (b), it can be observed that the errors decrease with the increase in injection interval time. That is because the temperature of the glue will rise when the injection time increases. Therefore, it is necessary to find a method of error compensation (Figure 13).

The longer the injection time and the faster the spray frequency are, the higher the temperature of the injection chamber caused by the friction between the glue, the valve body, and the needle, which leads to the lower viscosity of the glue. As a result, the volume of the droplet will be larger, and the difference between actual and desired droplet becomes larger and larger, which affects the consistency and accuracy of the droplet.
Assuming the driving signal is square wave with duty \( \alpha \) and period \( T \), the rising and falling time of the needle is \( \alpha T \) and \( (1 - \alpha)T \), respectively. Thus, the volume of the droplet can be rewritten as the following by equation (35)

\[
V_t = \alpha TQ_2 + (1 - \alpha)TQ_4 = \alpha T(Q_2 - Q_4) + TQ_4
\]  

(36)

According to equation (36), when the period is constant, the higher the duty cycle, the larger the volume of the droplets, so it can be adjusted by changing \( \alpha \). Assuming the actual value of the droplet volume is \( V_r \), the error denotes \( \Delta V = V_t - V_r \). We define the ratio between the desired and actual droplet volume as

\[
\beta = \frac{V_t}{V_r}
\]  

(37)
As can be seen from equation (37), in the first case \( V_r > V_t, \beta < 1, V_r \) will decrease by reducing \( \alpha \) to reduce the error \( \Delta V \). In the second case \( V_r < V_t, \beta > 1 \), raising the value of \( \alpha \) can decrease the error. As a result, the value \( \alpha \) should adjust according to \( \beta \), and its variation can be expressed as

\[
\Delta \alpha = (\beta - 1)\alpha
\]  

(38)

According to equation (38), we can change the duty cycle to eliminate the error. But we need determine the actual volume of droplets which varies with the injection frequency and time. Therefore, we adopt radial basis function (RBF) neural network to build the relationship between them, and it can predict the real-time change of the droplet volume.

To validate the effective of the compensation, the RBF neural network model can be gained from these sampling data, where the sampling frequency range is \([20–100 \text{ Hz}]\) in the increment of 5 Hz. Using the compensation method, the droplet volume before and after compensation is shown in Figures 14–16, which denotes

![Figure 12. Influencing factors of droplet volume: (a) radius of spray chamber, (b) glue supply pressure, (c) glue viscosity, and (d) turn-on time of hammer.](image-url)
the droplet volume errors and duty cycle change before and after compensation, respectively. As shown in Figure 14–16, we can observe that the error after compensation reduces obviously compared with before compensation from $[0.5\text{~mL}]$ to $[0.04\text{~mL}]$. These results showed that the proposed method can effectively reduce the error and improve the consistency of the droplet by micro-injection dispensing system.

**Conclusion**

In this article, a new type of micro-injection dispenser featuring compliant mechanism is presented. The proposed jetting dispenser was manufactured and tested to validate the prediction model describing the droplets size from the proposed
Figure 14. Droplet volume change before and after compensation.

Figure 15. Droplet volume errors before and after compensation: (a) error before compensation and (b) error after compensation.
dispensing system. The analytical results are in good agreement with the experimental results, which shows the correctness of the deduced volume estimation model. Furthermore, we presented a method compensating errors of droplets volume caused by the temperature increase in the long-time jetting process. The experimental results illustrate that the proposed method can effectively reduce the errors from $[-0.5 \sim 5 \mu L]$ to $[-0.04 \sim 0.08 \mu L]$, and the consistency of the droplets can be improved.

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