Dynamic characteristics of piezoelectric jetting dispenser with a double spring recovery system

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Abstract. Piezoelectric jetting dispenser is widely used in microelectronic packaging field. The amplification mechanism with flexible hinge is often used in the piezoelectric jetting dispenser. Because the dynamic performance of the dispenser is affected by the deformation of flexure hinge, a model using rigid body amplification mechanism and double spring recovery is proposed in this paper. The mathematical model of the recovery system is established and the dynamic analysis is carried out. The working characteristics of piezoelectric ceramics are analyzed. With the increase of load stiffness, the maximum output force increases and the maximum output displacement decreases. With the decrease of needle stroke, the pressing force between the needle and the nozzle increases. Based on the double spring recovery system, the ADAMS simulation model is established, and the influence of the pre-compression of the double springs on the pressing force between the needle and the nozzle is studied.

1. Introduction
Piezoelectric jetting dispenser has the characteristics of high frequency, high precision and nano-scale droplets dispensing [1, 2].

The driving system and the recovery system of piezoelectric jetting dispenser play an important role in dynamic performance and jetting performance. Because the output displacement of piezoelectric ceramics is too small to meet the dynamic performance, some experts have studied the amplification mechanism [3, 4]. Deng, Wang, Zhou and Li [5] have proposed a simplified analysis method for rhombic amplification mechanism. Bu, Lin and Huang [6] have put forward a piezostack-driven jetting dispenser with corner-filleted flexure hinge, and the working frequency can reach 400Hz. Based on piezoelectric principle, hydrodynamics and physical model, some experts have carried out simulation research on the system performance of piezoelectric jetting dispenser [7, 8]. Deng, Cui, Zhou and Li [9] have established the dynamic differential equation, and studied the dynamic performance of piezoelectric injection valve based on the Simulink simulation model.

Piezoelectric jetting dispenser is used in the industrial field, not only to meet the jetting performance, but also to meet the sealing performance. When the high voltage is applied to the piezoelectric stack and the amplifier is in the lower balance position, the pressing force between the needle and the nozzle is an important factor affecting the sealing performance. Referring to the previous literature, there is no research on the sealing performance.
In this paper, the ADAMS simulation model is established by combining the double spring recovery system model and the piezoelectric ceramic model under load. Based on the simulation model, the mechanical analysis of the piezoelectric jetting dispenser is carried out.

2. Physical model

The amplification mechanism periodically transfers the driving force from the piezoelectric ceramics to the needle, and the injection process is completed. The structural schematic diagram of the double spring recovery system is shown in Fig.1.

![Figure 1. Schematic diagram of physical model.](image)

The upper balance position is set to the initial position. In the initial state, the pre-compression of spring $k_1$ and spring $k_2$ is $x_1$ and $x_2$ respectively, providing preload force $F_g$ for the piezoelectric stack. The initial state is as follows:

$$x_0 = 0, \dot{x}_0 = 0$$  \hspace{1cm} (1)

The position coordinate in the vertical direction of the center of mass of the impactor is set as $x$. The value below the initial position is negative, and the value above the initial position is positive. The output force $F_{out}$ of the piezoelectric stack is as follows:

$$F_{out} = F_m + k_y x + m_s \ddot{x} + m_g g + F_g$$  \hspace{1cm} (2)

When the high voltage is applied to piezoelectric stack, an output force is supplied to the amplifier by the piezoelectric stack. The magnifying mechanism rotates around the rotating center and drives the needle downward. The piezoelectric injection system is divided into two parts: Part 1 and Part 2. The dynamic differential equation of Part 1 is as follows:

$$F_{out}l_2 + m_1gl + m_2gl_2 = F_Nl_2 - k_1(-x + x_1) l_2^2 - M_f = -J_0 \dot{x}'' - m_2l_2x'' - m_3l^2 x''$$  \hspace{1cm} (3)

The dynamic differential equation of Part 2 is as follows:

$$F_N' + m_3 g - k_2 (x + x_2) + Cx' = -m_3 x''$$  \hspace{1cm} (4)
The equilibrium equation at the lower equilibrium position is as follows:

\[
F_{\text{out}} + m_1 g + m_2 g + m_3 g = k_1 (-x + x_1) \frac{l_1}{l_2} + k_2 (x + x_2) + F_{c1} + F_{c2}
\]  

(5)

When the low voltage is applied to piezoelectric stack, the piezoelectric stack shortens, the amplification mechanism deflects upward and the needle moves upward. When the driving frequency of the piezoelectric stack is less than the maximum operating frequency of the piezoelectric valve, there is no separation between the needle and the nozzle. The dynamic differential equation of Part 1 is as follows:

\[
k_1 (-x + x_1) \frac{l_1^2}{l_2} - m_1 g l - m_2 g l_2 - M_f - F_{\text{out}} l_s + F_N l_2 = J_0 \frac{x''}{l_2} + m_2 l_2 x'' + m_3 l_2^2 \frac{x''}{l_2}
\]  

(6)

The dynamic differential equation of Part 2 is as follows:

\[
k_2 (-x + x_2) - m_3 g - C_2 x' - F_N' = m_3 x''
\]  

(7)

When the driving frequency of the piezoelectric stack is greater than the maximum operating frequency of the piezoelectric valve, the needle and the impactor separate during the upward movement. At this time, the dynamic differential equation of Part 1 is as follows:

\[
k_1 (-x + x_1) \frac{l_1^2}{l_2} - m_1 g l - m_2 g l_2 - M_f - F_{\text{out}} l_s = J_0 \frac{x''}{l_2} + m_2 l_2 x'' + m_3 l_2^2 \frac{x''}{l_2}
\]  

(8)

The dynamic differential equation of Part 2 is as follows:

\[
k_2 (-x + x_2) - m_3 g - C_2 x' = m_3 x''
\]  

(9)

The equilibrium equation at the upper equilibrium position is as follows:

\[
F_{\text{out}} + m_1 g + m_2 g + m_3 g = k_1 (-x + x_1) \frac{l_1}{l_2} + k_2 (-x + x_2) + F_{c2}
\]  

(10)

\(x_0\) is the position of the amplification mechanism with the preload; \(F_{\text{out}}\) is the output force of the piezoelectric stack; \(m_2\) is the equivalent mass of the piezoelectric stack; \(l_s\) is the distance between the piezoelectric stack and the rotation center; \(m_1\) is the mass of the amplification mechanism; \(m_2\) is the mass of the impactor; \(m_3\) is the mass of the needle; \(l\) is the distance between the centroid of the amplification mechanism and the rotation center; \(l_1\) is the distance between the plane spring and the rotation center; \(l_2\) is the distance between the impactor and the center of rotation; \(k_1\) is the stiffness of the plane spring; \(k_2\) is the stiffness of the spiral cylindrical spring; \(C_1\) is the equivalent damping when the needle moves downward; \(C_2\) is the equivalent damping when the needle moves upward; \(F_{c1}\) is the contact force between the needle and the nozzle; \(F_{c2}\) is the contact force between amplification mechanism and frame; \(F_N\) is the support force provided by the needle to the impactor; \(F_N'\) is the reaction force provided by the impactor to the needle; \(M_f\) is the friction torque at the rotation center; \(J_0\) is the moment of inertia of the amplification mechanism, which can be calculated by SolidWorks.

3. Working characteristics of piezoelectric stack
When the high voltage is applied to the piezoelectric ceramics without load, the piezoelectric stack extends to the maximum length \( L_{\text{max}} \), the output force is 0. When the load stiffness is infinite, the output displacement of the piezoelectric stack is 0 and the maximum output force \( F_{\text{max}} \) is obtained. When piezoelectric ceramic is used in piezoelectric jetting dispenser, it often works with elastic load. The schematic diagram of piezoelectric ceramic with elastic load is shown in Fig.2 (a).

Only considering the deformation of piezoelectric ceramic and the load spring, the working characteristics of piezoelectric ceramic are analyzed. As shown in Fig.2 (b), with the load stiffness from \( k_l \) increases to \( k'_l \), the maximum effective output force \( F_e' \) increases and the maximum output displacement \( \Delta L_0 \) decreases.

\[
F_e = F_{\text{max}} \cdot \left(1 - \frac{k_p}{k_l+k_p}\right) \quad (11)
\]

\[
\Delta L_0 = L_{\text{max}} \cdot \frac{k_p}{k_l+k_p} \quad (12)
\]

The tensile strength of piezoelectric ceramics is very low, so it is necessary to add preload in use. Preload \( F_p \) of load makes the piezoelectric stack deform. When the load stiffness does not change and the position of piezoelectric ceramic added with preload is the initial position, the maximum effective output force \( F'_e \) and the maximum output displacement \( \Delta L_1 \) remain unchanged. Therefore, \( F'_e = F_e, \Delta L_1 = \Delta L_0 \). When the initial position of the piezoelectric ceramic before deformation is selected as the initial position, the effective output displacement decreases. Therefore, \( \Delta L_1 < \Delta L_0 \).

![Figure 2.](image)

Based on the working principle of piezoelectric jetting dispenser, when the position of piezoelectric ceramic added with preload is selected as the initial position, the pressing force between nozzle and nozzle is analyzed. As shown in Fig.3, when the stroke of the needle is \( X_2 \), part of the output force of the piezoelectric stack is used to overcome the deformation force \( F_q \) of the load, and the other part is used to overcome the pressing force \( F_m \) between the needle and the nozzle. When the load stiffness is constant, the pressing force between the needle and the nozzle increases as the stroke of the needle decreases from \( X_1 \) to \( X_2 \).
4. Simulation model
Adams is a multi-body dynamic simulation software. The three-dimensional model created by SolidWorks is imported into Adams, and the virtual machine model is created by adding constraints, contacts and forces. The force and reaction force curves can be obtained through dynamic simulation, and the system force analysis can be carried out [10].

The ADAMS simulation model is created based on the double spring recovery system model. The recovery system consists of spring $k_1$ with a stiffness of 60 N/mm and spring $k_2$ with a stiffness of 17 N/mm. A p-887.91 type multilayer piezoelectric ceramic driver produced by PI company is used for the simulation model. According to the parameters of piezoelectric ceramic, the relationship among output force $F_{out}$, working voltage $U$ and output displacement $S$ can be obtained, as shown in Fig.4.

\[ F_{out} = \text{step} \left( \sin \left( 2 \times \text{time} \times 500 \times \pi \right), -0.4, 0, 0.4, 1580 \right) \]  

\[ (13) \]
The sealing performance of piezoelectric jet valve plays an important role in industrial application. The pressing force between the needle and the nozzle is an important factor affecting the sealing performance. Based on the ADAMS model, the mechanical analysis of a double spring recovery system can be carried out. The control variable method is used for two simulation analysis. Simulation (1): the preload force of spring $k_2$ is set to 22 N, and when the preload of spring $k_1$ is 10 N, 22 N, 34 N, 46 N respectively, the mechanical analysis is shown in Fig.6. Simulation (2): the preload force of spring $k_1$ is set to 30 N, and when the preload of spring $k_2$ is 12 N, 18 N, 24 N, 30 N respectively, the mechanical analysis is shown in Fig.7.

As shown in Fig.6 (a) and Fig.7 (a), with the increase of preload of spring $k_1$ and spring $k_2$, the preload of the piezoelectric stack increases, and the upper balance position moves up, so the stroke of the needle increases. As shown in Fig.6 (b) and Fig.7 (b), when the high voltage is applied to the piezoelectric stack and the amplification mechanism is in the lower balance position, the output force of the piezoelectric stack is 890 N. The output force does not change with the pre-compression of spring $k_1$ and spring $k_2$. When the low voltage is applied to the piezoelectric stack and the amplification mechanism is in the upper balance position, the output force of the piezoelectric ceramic is equal to the preload provided by the double springs. As shown in Fig.6 (c) and Fig.7 (d), when the amplification mechanism is in the lower balance position, with the increase of the preload of spring $k_1$, the driving force provided by the impactor to the needle decreases, and the pressing force between the needle and the nozzle decreases. When the amplification mechanism is in the upper balance position, with the increase of the preload of spring $k_1$, the contact force between the impactor and the needle does not change with the pre-compression of spring $k_1$. As shown in Fig.7 (c) and Fig.7 (d), when the magnifying mechanism is in the lower balance position, with the increase of pre-compression of spring $k_2$, the driving force provided by the impactor to the needle remains unchanged, and the contact force between the needle and the nozzle decreases. When the amplification mechanism is in the upper balance position, the contact force between the striker and the spray needle increases with the increase of the pre-compression of spring $k_2$. 

**Figure 5.** The ADAMS simulation model.
Figure 6. Simulation analysis 1.

Figure 7. Simulation analysis 2.
5. Conclusion
In this paper, a double spring recovery system model is provided for the high-performance piezoelectric jetting dispenser, and the dynamic differential equations are established to analyze the dynamic performance of the piezoelectric injection valve. Based on the double spring recovery system, the ADAMS simulation model is created. Combined with the analysis of the working characteristics of the piezoelectric stack, the influence of the pre-compression of the double spring on the pressing force between the needle and the nozzle is analyzed, which provides a new method for the study of the sealing performance of the piezoelectric jetting dispenser.

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References
[1] C. Zhou, J.-a. Duan, G. Deng, J. Li, A Novel High-Speed Jet Dispenser Driven by Double Piezoelectric Stacks, IEEE Transactions on Industrial Electronics, 64 (2017) 412-419.
[2] Q. H. Nguyen, S. B. Choi, J.-D. Kim, The design and control of a jetting dispenser for semiconductor electronic packaging driven by a piezostack and a flexible beam, Smart Materials and Structures, 17 (2008).
[3] A.M. Sohail Iqbal, A review on MEMS based micro displacement amplification mechanisms, Sensors and Actuators A: Physical, 300 (2019) 111666.
[4] C. Zhou, J. Li, J.-A. Duan, G. Deng, Direct-Acting Piezoelectric Jet Dispenser With Rhombic Mechanical Amplifier, IEEE Transactions on Components, Packaging and Manufacturing Technology, 8 (2018) 910-913.
[5] G. Deng, N. Wang, C. Zhou, J. Li, A Simplified Analysis Method for the Piezo Jet Dispenser with a Diamond Amplifier, Sensors (Basel), 18 (2018).
[6] Z. Bu, S. Lin, X. Huang, A novel piezostack-driven jetting dispenser with corner-filleted flexure hinge and high-frequency performance, J. Micromech. Microeng. (UK), 28 (2018) 075001 (075010 pp.).
[7] Y. Yang, S. Gu, Q. Lv, J. Liu, Z. Yang, C. Li, H. Tian, Influence of needle impact velocity on the jetting effect of a piezoelectric needle-collision jetting dispenser, AIP Advances, 9 (2019).
[8] J.Z. Shizhou Lu, Yong Liu, Hai Zheng, Chenliang Ren, Wei Liu, Droplet formation study of a liquid micro-dispenser driven by a piezoelectric actuator, Smart Materials and Structures, 28 (2019) 055003 (055009 pp.).
[9] G. Deng, W. Cui, C. Zhou, J. Li, A piezoelectric jetting dispenser with a pin joint, Optik, 175 (2018) 163-171.
[10] X.Z. Bai, Xutang; Liu, Wenjian, Dynamic simulation of auto-centralizer for horizontal well traction robot based on ADAMS Shiyou Kantan Yu Kaifa, 37 (2010) 104-110.