Implementation and experiment of a novel piezoelectric-spring stage for rapid high-precision micromotion

Lanyu Zhang¹ · Jian Gao¹

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Abstract

A precision micromotion stage is significant in the microelectronics-manufacturing field to realize high-performance tasks. The output position error and limited frequency response influence the working performance and efficiency of the micromotion stage. A novel piezoelectric-based (PZT) reciprocating micromotion stage with a special spring-PZT structure is proposed in this paper to cater to the high manufacturing demands and achieve rapid precision micromotion performance. This structure is designed to use a high-stiffness spring element as the flexure deformation structure, by utilizing the linearity of the spring, for achieving precise output/input ratio and high-frequency response. The feasibility of the micromotion stage is explored through theoretical analyses, including a dynamic response analysis, frequency response analysis, output displacement, and rapidity analysis of the specialized spring-PZT structure. For the inherent hysteresis challenge of the PZT-based structure, a feedforward subdivided proportional–integral–derivative method is adopted for system implementation. Subsequently, an optimal design of the stage is established, and the expected motion performance is verified experimentally. Finally, a series of experiments in terms of output ratio property analysis, dynamic hysteresis characterization, tracking error performance, and response rapidity are conducted for different micromotion frequencies and strokes. It is indicated that the stage can achieve nanometre-level precision and high-frequency micromotion simultaneously, which could be applied in the microelectronics manufacturing for rapid precision micromotion operations.

1 Introduction

A micromotion stage is a significant motion component in microelectronic packaging manufacturing to accomplish high-frequency accurate reciprocating operations (He et al. 2019; Llewellyn-Evans et al. 2020; Gwon et al. 2014; Zhang et al. 2018a, b; Zhang et al. 2015). For example, the micromotion stage of chip wire bonding equipment should rapidly achieve nanometre-level position accuracy within the 50 ms cycle time of the packaging process (Zhang et al. 2017; Kim et al. 2006). Currently, the requirements for both high precision and efficiency in microelectronic packaging manufacturing are continuously improving (Li and Huang 2012; Khan et al. 2018). Improving the micromotion accuracy without sacrificing the high operating frequency has been a critical pursuit.

A pioneering approach in packaging equipment is the use of piezoelectric (PZT)-based devices to play the PZT advantages of high-precision motion resolution, rapid reciprocating motion, and high-frequency response (Zhang et al. 2018a, b; Suzuki and Soga 2012; Wang et al. 2019). However, owing to the PZT inherent hysteresis effect and the motion nonlinearity of the device structure, the micromotion error within these PZT-based devices may offset their motion accuracy and influence the packaging operation quality (Mohammadzaheri and Grainger 2012; Zhou et al. 2016; Polit and Dong 2011).

To achieve a rapid high-precision micromotion of the PZT-based devices, several methods have been implemented and can be categorized as either control strategy or structure design methods. For the control strategy category, a method for establishing an error-compensation feedforward control model is widely studied, and it is effective for ensuring the precision micromotion implementation of the PZT-based mechanism (Ghafarirad et al. 2014; Hassani et al. 2014). However, since the motion error of the micromotion device is amount-variant and time-variant in actual application, an accurate and adaptive implementation is necessary for the

✉ Jian Gao
gaojian@gdut.edu.cn

¹ State Key Laboratory of Precision Electronic Manufacturing Technology and Equipment, Guangdong University of Technology, Guangzhou 510006, China

feedforward model compensation method (Dong et al. 2014; Keang and Devasia 2007). Therefore, a method for a proportional–integral–derivative (PID) closed-loop feedback control combined with the feedforward compensation model has been studied in industrial applications and found to be effective for further reducing the motion error of the PZT-based devices under rapid micromotion. Liu et al. (2004) presented a model reference control method that combined a feedforward compensation model and a PI controller for a PZT micropositioning mechanism, which can be used in microelectronic semiconductor manufacturing. This method showed that dozens of nanometre-level tracking errors could be obtained under a 0.06 m/s velocity and a 4 Hz motion frequency. Tang et al. (2018) designed a PZT-based micromotion operator for the chip high-speed precision packaging, which combined a transfer-function feedforward model and a PID controller. The experiments showed that the method could help the operator in achieving a 0.2 μm positioning accuracy under a 10 Hz motion frequency and a 0.12 mm/s velocity. Hafea et al. (2014) designed a PZT-actuated precision positioning mechanism for the applications of high response positioning; a feedforward compensation model combined with a PID controller compensated for the micromotion error. Based on experimental results, the maximum position error could be reduced from 12.43 μm to 0.127 μm under a motion frequency of 1 Hz at a velocity of approximately 0.15 mm/s. Moreover, the improved PID control method has been studied and applied in industrial applications for enhancing the effects of conventional PID control, which is an effective approach to improve the motion accuracy of the micromotion mechanism by combining the model compensation approach (Wang et al. 2010; Dinh et al. 2018; Zhou et al. 2020).

The structure design method is the second approach used to improve the PZT-based mechanism motion precision performance. Various micromotion mechanisms are widely used with the PZT element for achieving the desired micromotion. However, the motion accuracy of slightly flexible deformation structures of these mechanisms is still limited in high dynamic motion applications. This is because the deformation ratio errors of the flexure linkage will affect the micromotion linearity and precision in actual industrial applications (Liu et al. 2018). Dirksen et al. (2013) considered the dynamic applications with the flexure-based mechanism structure and analysed the change of the micromotion ratio of the hinge structure to provide an optimal structure design approach. Nijenhuis et al. (2020) investigated the inadvertent stress of misalignment with an over-constrained design for a PZT micromotion mechanism to improve the performance of the structure with a highly repetitive movement. Currently, the feedforward PID related and structure design methods are the main

approaches for the micromotion devices in the microelectronic manufacturing field.

For achieving a high-precision micromotion output with a high operating frequency for the microelectronic packaging manufacturing, a rapid high-precision micromotion method with a PZT-based stage is proposed in this paper. Specifically, by means of utilizing the linearity of the spring element as the flexure deformation linkage, a special spring-PZT micromotion structure is designed for the stage to achieve a stable precision displacement ratio between the input signal and the output. The output characteristic of high-frequency response, the displacement, and the rapidity of the proposed structure is determined. Thus, the motion accuracy and rapidity of the designed micromotion stage can be ensured simultaneously. Considering the hysteresis of the PZT-based micromotion mechanism, a feedforward PID method is adopted for the system implementation. The genetic algorithm is also used for the PID parameters auto-tuning to obtain the corresponding rapid and accurate micro-actions in the implementation process. The experimental results showed that the designed PZT-spring stage could achieve a stable high-precision output performance with high-frequency. The positioning precision of a nanometre can be obtained under different micromotion frequencies, strokes, and waveforms.

The remainder of this paper is arranged as follows: First, the design of the micromotion stage and its working procedure is described in Sect. 2. In Sect. 3, a series of theoretical analyses are presented whereas the system implementation method is described in Sect. 4. The basic experimental setup is specified, and the micromotion performance of the stage is experimentally verified in Sects. 5 and 6, respectively. The achievements of this work are summarized in Sect. 7.

2 Proposed spring-PZT micromotion stage

The construction of the designed micromotion stage and the specialized spring-PZT structure are shown in Figs. 1 and 2, respectively. The PZT actuator drives the motion of the stage. A high-stiffness spring element is designed in this stage to incorporate the motion of the PZT. The fixed axis is used to tightly connect the stage, and provide a fulcrum for the micromotion. The grating element and encoder are used to record the displacement of the stage.

The working procedure of the micromotion stage is shown in Fig. 3.

- 1) In the beginning, the stage is located at the initial position.
- 2) For realizing the micromotion, the stage is actuated and moved from the initial position to the target

Fig. 1 Components of the micromotion stage

Fig. 2 Designed spring-PZT structure of the micromotion stage

position through application of driving force to the PZT.

- 3) In the extension procedure of the stage, the positioning error around the target position can be dynamically compensated for through the cooperation of the spring and the PZT based on the real-time error feedback of the grating encoder. If the stage passes over the target position (as shown in Fig. 3b), the PZT then shrinks by the corresponding displacement. If the stage does not reach the target position (as shown in Fig. 3b'), the PZT extends the corresponding displacement.
- 4) In the retraction process, the stage can be actuated to move backward through control of the PZT and the extension of the spring, as shown in Fig. 3c. Then, the stage can be brought back to the initial position to keep it ready for the next micromotion by repeating the above process.

3 Dynamic analysis

The dynamic analysis of the stage actuated by the PZT is conducted to verify the dynamic response of the stage with the designed spring-PZT structure. Figure 4 shows the

Fig. 3 Working procedure of the micromotion stage

established dynamic model of the micro-positioning stage. While the actuator is fixed to the stage, the spring is initially compressed by a suitable amount of compression range A_s . Thus, a contact force forces the stage to remain in contact with the PZT and precisely follow its actuation. The differential equation of the dynamic response of the stage can be obtained as:

$$M\ddot{x} = F_z - K_s(x + A_s) - C_s\dot{x} - \mu\dot{x} \quad (1)$$

where M is the collective mass of the micromotion structure including the stage, nut, and PZT with its sleeve; K_s and C_s are the stiffness and damping coefficient of the spring, respectively; and μ is the viscosity coefficient

Fig. 4 Dynamic model of the stage micromotion

between the stage and the guide. The stage output displacement x is actuated under the application of the driving force F_z of the PZT. Thus, based on the Laplace transform, we can obtain the transfer function of the stage and the PZT to reflect the dynamic response performance of the stage under the fast and dynamic PZT input.

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + (C_s + \mu)s + K_s} \quad (2)$$

where, $X(s)$ and $F(s)$ are the Laplace transform of the displacement x and the resultant force $F_z - K_s A_s$, respectively.

3.1 Frequency response analysis

For clarifying the frequency response characteristic of the proposed structure, the system natural frequency must be derived; this is a vital factor in defining the frequency expression. The system dynamic differential equation with no-damping and no-force state can be expressed as:

$$M\ddot{x} + K_s x = 0 \quad (3)$$

The general solution of this second-order linear differential equation can be expressed as:

$$\begin{cases} x = A \sin(\lambda t + \varphi) \\ \dot{x} = \lambda A \cos(\lambda t + \varphi) \\ \ddot{x} = -\lambda^2 A \sin(\lambda t + \varphi) \end{cases} \quad (4)$$

where A is the vibration amplitude of the stage; λ is the self-vibration frequency; t is the time; and φ is the phase angle.

Using Eq. (4), the system self-vibration motion of the Eq. (3) can be replaced as:

$$(K_s - \lambda^2 M)x = 0 \quad (5)$$

For satisfying Eq. (4) for any displacement value x , the self-vibration coefficient λ should be solved using the equation

$$|K_s - \lambda^2 M| = 0 \quad (6)$$

Consequently, the solution of Eq. (6) is $\lambda^2 = \frac{K_s}{M}$.

Thus, the relationship of the natural frequency response of the stage and the spring stiffness adjusting can be confirmed by the structural parameters. The stiffness of the

spring was adopted with $15 \text{ N}/\mu\text{m}$, and the mass of the stage was determined with 0.6 kg . Then, the natural frequency f of the system can be calculated as

$$\begin{cases} \lambda = 5000 \text{ rad/s} \\ f = 796.2 \text{ Hz} \end{cases}$$

The system natural frequency response performance can be raised by increasing the spring stiffness K_s , which is used to increase the motion bandwidth and avoid a resonance phenomenon. Thus, a spring high in stiffness is designed for achieving a high-frequency motion output and will improve the working efficiency of the stage.

3.2 Output displacement analysis

Since the PZT in the proposed micromotion structure is used under restraint in this study, the output displacement of the stage with the designed spring-PZT structure is analysed to precisely clarify the stage output. According to the output characteristics of the PZT, its displacement is proportional to the applied voltage U_p with a displacement amplification ratio A_p , which can be expressed as:

$$x_p = U_p \cdot A_p \quad (7)$$

In the proposed spring-PZT micromotion structure, the PZT is compressed when it is actuated to extend a displacement. Based on the designed micromotion structure, the relationship between the actual output displacement for the stage and the input displacement amount in the PZT is

$$x_a = \frac{x_p \cdot K_z - F_l}{K_z + K_s} \quad (8)$$

where K_z is the stiffness of the PZT; F_l is the preload on the PZT from the stage; x_a is the actual output displacement for the stage; x_p is the input target displacement of the PZT. Therefore, to improve the positioning performance of the micromotion stage, the relationship between the actual output displacement for the stage and the input displacement for the PZT actuator will be considered.

3.3 Output rapidity analysis

To achieve a rapid micro-action, the response time of the stage with the PZT actuation is analysed. The response speed of the PZT is fast in the case of the inverse piezoelectric effect. By applying an applied voltage and a current, the action time of the PZT is approximately one-third of its resonant frequency (Wang et al. 2009).

$$t_p \approx \frac{1}{3f_p} \quad (9)$$

Here, t_p is the response time of the PZT, and f_p is the action resonant frequency of the PZT.

Owing to the stage mass acts on the PZT, the frequency f_p will be changed as follows:

$$f_p = \frac{1}{2\pi} \sqrt{\frac{K_p}{\frac{1}{3}M_p + M_{pl}}} \quad (10)$$

where K_p and M_p are the stiffness and the mass of the PZT, respectively. M_{pl} is the stage mass acting on the PZT and the mass of the PZT installation structure.

Thus, the response time can be calculated by the PZT and stage parameters and provide a reference for analysing the output rapidity of the stage.

4 System implementation of the micromotion stage

To overcome the hysteresis effect of the PZT-based mechanism and achieve a precision implementation process for the stage, a feedforward subdivided PID (FSPID) control method is adopted in the system. The implementation scheme is shown in Fig. 5.

From Fig. 5, $u_c(t)$, $u_r(t)$, $u_p(t)$, $u(t)$, and $x(t)$ denote the planned command signal, reference signal of the feedforward model, PID control output, control output signal for the stage, and actual output of the stage, respectively.

1) Feedforward compensation model

Considering the inherent hysteresis effect in the PZT actuators, a hysteresis modelling is conducted to correct the stage output amount. The detailed model is established using the conventional Preisach model method (Choi et al. 2005; Han et al. 2003). The Preisach compensation method is based on an established hysteresis characteristic model, which is created using the experimental results of the micromotion stage, and then inverses the model as a feedforward signal reference.

2) Subdivided PID

To enhance the implementation precision of the feedforward compensation model, a subdivided PID (SPID) closed-loop control is also employed in this study. The conventional PID control method is widely applied in the packaging industrials. However, its motion accuracy is still

limited under the higher requirements for the high-density high-precision packaging manufacturing because of the simple implementation process and motion mode. Based on the obtained feedforward compensation model, the SPID approach is used to subdivide the implementation process to obtain a precision micromotion.

The displacement signal for the micromotion stage is subdivided instead of how it is processed in the case of the direct displacement signal input of the conventional PID control. The details pertaining to the SPID method are introduced as follows. The proportional part of the SPID controller is adopted as:

$$u_p(t) = C_p(s(t) - c(t)) \quad (11)$$

where C_p is the proportional coefficient of the conventional PID control, and $s(t)$ is the subdivided target values with a straight motion target arrangement; $c(t)$ is the current position value of the platform at the time t , and $|s(t) - c(t)| < |e(t)|$, $e(t)$ is the error signal of the target value and the current position value of the stage.

The integral part with the SPID controller is

$$u_i(t) = \begin{cases} C_i \int e(t); & \text{if } e(t) \leq \varepsilon \quad l = t, t + \tau, \dots, t + \tau k \\ 0; & \text{if } e(t) > \varepsilon \quad t = 0, 1, \dots, t \end{cases} \quad (12)$$

where C_i is the integral coefficient of the conventional PID control; ε is the integral saturation threshold, which is added in the equation to avoid the integral saturation problem; τ is the control signal time; k is the number of the time to reach the target.

The derivation part of the SPID controller is

$$\begin{aligned} u_d(t) &= C_d[(s(t) - c(t)) - (s(t-1) - c(t-1))] \\ &= C_d[(s(t) - s(t-1)) - (c(t) - c(t-1))] \end{aligned} \quad (13)$$

where C_d is the derivation coefficient of the conventional PID control.

Based on the above SPID controller, the motion signal possesses the subdivision treatment characteristic, which can be applied to every motion output loop of the micromotion stage with real-time feedback.

3) PID parameters tuning

The genetic algorithm (GA) is a search technique that manipulates the coding representation of a parameter set to search a near-optimal solution through mutation and selection among the potential solutions (Lazarevic et al. 2013; Zhang et al. 2009). In this study, GA is used to obtain the optimal solution of a PID parameter in the closed-loop feedback of the micromotion stage. In the coding implementation, each PID parameter is encoded as a vector of real numbers with the same length as that of the solution vector, which can be shown as:

Fig. 5 Implementation of the micromotion stage

$$\begin{aligned}
000000 \dots 0000 &= 0 \rightarrow U_1 \\
000000 \dots 0001 &= 1 \rightarrow U_1 + \delta \\
000000 \dots 0010 &= 2 \rightarrow U_1 + 2\delta \\
&\vdots \\
111111 \dots 1111 &= 2^l - 1 \rightarrow U_2
\end{aligned} \quad (14)$$

where U_1 and U_2 are the maximum and minimum ranges of the objective parameters, respectively; l is the length of the binary coding; δ is the coding interval value, which can be expressed as:

$$\delta = \frac{U_2 - U_1}{2^l - 1} \quad (15)$$

Based on the coding process, the potential solutions for searching the optimal PID parameter are established, and the decoding equation for a coding parameter ($b_l b_{l-1} b_{l-2} \dots b_2 b_1$) can be expressed as:

$$D = U_1 + \left(\sum_{i=1}^l b_i \cdot 2^{i-1} \right) \cdot \frac{U_2 - U_1}{2^l - 1} \quad (16)$$

Based on the requirements of packaging manufacturing, the micromotion accuracy and rapidity of the stage are the key evaluation factors, which should be improved with the closed-loop control method. Thus, an evaluation function including the motion accuracy and action time factors is provided to measure the quality of the solution in the GA evaluation process, which is shown as:

$$E(t) = \int_0^\infty (\sigma_1 |e(t)| + \sigma_2 |e(t)|) dt + \sigma_3 t_r \quad (17)$$

where $e(t)$ is the system error at time t ; t_r is the motion rising time; and σ_i ($i = 1, 2$) are evaluation weight coefficients.

Under the rapid action requirement, an evaluation item of overshooting is added in the evaluation equation to avoid the overshoot error in the micromotion process. Equation (17) can be expressed as:

$$\begin{cases} E(t) = \int_0^\infty (\sigma_1 |e(t)| + \sigma_3 |e_o(t)|) dt + \sigma_2 t_r; & \text{if } e_o(t) < 0 \\ E(t) = \int_0^\infty (\sigma_1 |e(t)|) dt + \sigma_2 t_r & ; \text{if } e_o(t) \geq 0 \end{cases} \quad (18)$$

where $e_o(t) (= o(t) - o(t-1))$ is the value of overshooting; $o(t)$ is the output of the controlled objective; σ_3 is the evaluation weight coefficient; $\sigma_3 > \sigma_1$. The fitness function based on the evaluation equation is expressed as:

$$F = \frac{1}{E(t) + 1} \quad (19)$$

Depending on the GA coding and the evaluation equation, the search process for the optimal PID parameters is conducted with the genetic mechanism of selection,

crossover, and mutation for the potential solutions. In this study, an improved application method of crossover and mutation, which utilizes a multi-point operation method for the crossover and mutation process, is adopted as shown in Fig. 6. The flowchart of the optimization searching process with the GA for the PID parameters is shown in Fig. 7.

5 Experimental setup

An overview of the experimental setup is displayed in Fig. 8, and the details of the stage and the key elements are determined and presented in Table 1.

An absolute grating encoder (HEIDENHAIN LIC4015) with an input frequency of at most 500 kHz and a resolution of 1 nm was used to record the position of the stage. A data acquisition card (NI PCI-6289) is utilized to collect the position data from the grating encoder and transform the control signal into a power-amplified signal, and then into the controller of the PZT actuator (Pst 15077). The applied voltages for the PZT actuator control are simulated through a rapid prototyping system dSPACE at a sampling frequency of 2 kHz. A light displacement sensor (MTI-2100, MTI) is used to examine the positioning following the performance of the stage and compare it with the effects of the grating encoder. To avoid the vibrations, all the devices and units are mounted on a vibration isolation table (Newport, Inc.).

6 Experimental results and analysis

6.1 Open-loop tests

The open-loop tests are conducted to characterize the output properties and the response performance with a high frequency of the stage. For establishing the feedforward compensation model, the micromotion performance is also tested under different stroke frequencies.

1) Working frequency and output displacement ratio

The output performance of the stage with a high frequency is implemented. Figure 9 shows the output response of the stage actuated by a sinusoidal signal with a

Fig. 6 Multi-point operation method for the crossover process and mutation process

Fig. 7 Flowchart of the optimization searching process with the GA for the PID parameters

Fig. 8 Experimental setup of the designed micromotion stage

high frequency of 400 Hz and an input displacement of 3 μm . The experimental result shows that the stage can loyally respond to a high-frequency motion with stable position errors. The output displacement indicates the position error (within 0.44 μm) between the actual output displacement and the target displacement (input misplacement signal). The error mainly arises from the preload effect of the spring-PZT structure, which corresponds with the theoretical displacement analysis.

Subsequently, the displacement ratio relationship of the actual output of the stage and the input target displacement is also analysed with the test. Figure 10 displays the displacement ratio (the ratio of actual displacement to input

displacement), which is actuated by a sinusoidal signal at a frequency of 50 Hz and a displacement of 3 μm . The result shows that the displacement ratio with this designed spring-PZT stage structure is almost a stable value of 0.88, which indicates that the stage has a property of stable displacement output relationship in the micromotion process. The response result of the displacement ratio also reflects that the designed spring-PZT micromotion structure can overcome the complex time-varying and stiffness-varying challenges that occurred in the micromotion output process.

2) Micromotion performance at different strokes and frequencies

The detailed hysteresis characterizations of the stage with different displacements and frequencies are analysed to establish the feedforward compensation model.

Figure 11 shows the responses of the stage under different micromotion displacements. In the experiments, a sinusoidal signal with a constant frequency (400 Hz) and different amplitudes are applied to the PZT. It can be seen that the hysteresis loop shape is dependent on the input displacement amplitude. The larger the amplitude of the input displacement, the wider the hysteresis loop. Similarly, an input signal with a constant displacement (3 μm) and different frequencies is also applied to the PZT to test the performance of the stage. The responses of the stage are depicted in Fig. 12. It can be observed that the shape of the hysteresis loop is also dependent on the frequency of the input signal. When the frequency of the input displacement is high, the output hysteresis effect becomes sufficient.

Depending on the above analyses and tests of the stage output performance with the open-loop test, the results indicate that the position accuracy and hysteresis effect are vital to the micromotion performance of the stage. To solve these challenges, the closed-loop control strategy is presented in the following section.

6.2 Closed-loop tests

To validate the closed-loop micromotion performance of the proposed stage and achieve a rapid high-precision micromotion, the experiments for the designed FSPID method are conducted. The adopted implementation method is compared with the effects of the conventional closed-loop PID method. As shown in Fig. 13, the PID method is programmed using the MATLAB/Simulink software and downloaded to the dSPACE control system. The parameters of the PID implementation process with the GA tuning in the experiments are shown in Table 2.

1) Micromotion performance of the stage at different frequencies

Table 1 Parameters of the micromotion stage

Item	Value/material
Size of the stage (length × width × height) (mm ³)	120 × 70 × 8
Size of spring (wire/diameter/length) (mm)	2/17/25
Mass of stage (kg)	0.6
Stiffness of spring (N/μm)	15
Material of stage platform	Iron
Material of spring	Spring steel
Stroke of PZT (μm)	4
Stiffness of PZT (N/μm)	120
Resonance frequency of PZT (kHz)	40
Maximum/nominal voltage of PZT (V)	– 30–150/0–150
Nominal pull/trust of PZT (N)	300/1800
Linearity of PZT (%)	0.1

Fig. 9 Open-loop test of the stage with a micromotion frequency of 400 Hz **Fig. 11** Hysteresis performance of the open-loop test of the stage with different output displacements **Fig. 10** Output displacement ratio of the open-loop test of the stage **Fig. 12** Hysteresis performance of the open-loop test of the stage with different motion frequencies

As demonstrated in Figs. 13 and 14, comparisons of the output performance of the stage with and without the FSPID method are conducted to examine the effects of the adopted FSPID method for the designed stage at different frequencies. The experimental results are listed in Table 3. In the experiments, the input displacement is set to 3 μm, which is kept constant during the experiments. As shown in Table 3, using the FSPID method results in a 55.6% and 42.9% improvement in position maximum error and variance error, respectively, with a frequency of 50 Hz in the micromotion, and achieves a 40% and 39.1% improvement

in position maximum error and variance error, respectively, with a motion frequency of 400 Hz.

2) Effects of the adopted closed-loop implementation method on the stage hysteresis

The hysteresis performance of the stage is evaluated depending on the above-mentioned experiments. Figure 15 shows the hysteresis performance of the closed-loop stage motion with and without the FSPID method at different frequencies.

Fig. 13 Effects of the FSPID method for the micromotion stage at the motion frequency of 50 Hz

Table 2 Parameters of the adopted FSPID method

Item	Value
C_p	2
C_i	0.1
C_d	0.1
Range of C_p in GA	[0, 100]
Range of C_i in GA	[0, 100]
Range of C_d in GA	[0, 100]
G_n (Number of the generation in GA)	100
G_s (Size of every generation in GA)	80
k (Size of the coding in GA)	10
P_c (Probability of crossover)	0.6
P_m (Probability of mutation)	0.1
ε	1

The experimental results in Fig. 15 showed that the hysteresis of the micromotion stage could be observably improved with the adopted closed-loop motion method through a comparison with the open-loop tests in Sect. 6.1, and effectively improved through a comparison with the conventional PID control. The hysteresis error can be controlled within 1.5% when the micromotion frequency is set to 400 Hz.

3) Micromotion performance of the stage at different displacements

Fig. 14 Effects of the FSPID method for the micromotion stage at the motion frequency of 400 Hz

The stage micromotion with and without the FSPID method is compared at different micromotion strokes to further examine the effects of micromotion performance. The experimental results at different displacements (from 1 μm to 3 μm) are shown in Fig. 16. The other movement parameters are kept constant in these experiments. Based on the results, it can be observed that the stage can achieve precision micromotion with a mean error of 33 nm at different strokes. Simultaneously, the output micromotion can also be kept in a high frequency of 400 Hz.

4) Micromotion rapidity verification of the stage

Rapid micromotion performance is another key factor to evaluate the designed stage. The micro-actions time of the stage with and without the FSPID method is examined, and the results are shown in Fig. 17 and Table 4. The other movement parameters are also kept constant in these experiments. From the experimental results in Fig. 17, it can be seen that the FSPID method for the stage can effectively improve the precision performance and shorten the micromotion action time through a comparison with the PID control. The adopted implementation method can result in a rapid micromotion of 23 ms for the stage at the stroke of 1 μm .

Table 3 Effects of the FSPID method for the micromotion stage at the motion frequencies

Frequency	Motion error					
	Maximum (nm)		Improvement (%)	Variance (nm)		Improvement (%)
	Without FSPID	With FSPID		Without FSPID	With FSPID	
50	9	4	55.6	14	8	42.9
100	16	9	43.8	20	12	40
400	40	24	40	46	28	39.1

Fig. 15 Hysteresis effects of the FSPID method for stage micromotion with different motion frequencies, (a) With the frequency of 50 Hz, (b) With the frequency of 100 Hz, and (c) With the frequency of 400 Hz **Fig. 16** Effects of the FSPID method for the micromotion stage at different displacements

7 Conclusion

This paper presented a rapid precision micromotion stage with a special PZT-spring structure. The construction of the structure and the micromotion working procedure of the stage were described. With respect to the characteristics of

(a) Without the FSPID method **(b)** With the FSPID method**Fig. 17** Micromotion rapidity performance of the stage with and without the FSPID method

the designed PZT-spring structure, the theoretical analyses including the dynamic modelling, the frequency response analysis, the output displacement, and rapidity were illustrated for ensuring a rapid precision micromotion output. When the proposed stage was implemented during testing, a simple and effective FSPID method was adopted for the PZT-spring hysteresis. Several experiments were conducted at different micromotion frequencies, strokes, and action speeds. The results showed that the motion rapidity and precision of the stage could be ensured simultaneously. The stage can achieve 30 nm micromotion accuracy and a high-frequency motion of 400 Hz. The micromotion stage can be widely applied in microelectronic manufacturing for rapid precision micromotion operations.

Table 4 Effects of the adopted FSPID method on micromotion rapidity of the stage

Target position (μm)	Step response time (ms)						
	Forward action process time		Improvement (%)	Backward action process time			Improvement (%)
	Without GAND	With GAND		Without GAND	With GAND		
1	66.9	23.4	65	70.6	25.7	63.6	
2	60.7	22.2	63.4	71.3	26.2	63.3	
3	65.8	23.8	63.8	71.8	25.9	64.2	
4	59.6	21.7	63.3	70.9	25.9	63.5	

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