A Novel Decoupled Flexure Nanopositioner with Thermal Distortion Self-elimination Function

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Abstract—Flexure nanopositioner is usually utilized to compensate the alignment deviation in the process of Micro/mini LED chip repairing. However, thermal distortion effect always reduces the alignment accuracy of the precision positioning system, which will seriously affect the chip repairing quality. The motivation of this work is to develop a novel decoupled flexure nanopositioner with thermal distortion self-elimination function. The thermal distortion self-elimination performance is achieved via three flexible connection modules (FCM), in which the thermal stress can be automatically eliminated. Firstly, the design, modeling and optimization of the proposed flexure nanopositioner are presented. Then, theoretical analysis in terms of thermal deformation relationship derivation and whole mechanism compliance modeling are carried out, respectively. In addition, aiming for minimizing thermal distortion of the nanopositioner, the FCM is optimized by the genetic optimization algorithm (GA) and FEA evaluations. Finally, a series of validation experiments including displacement decoupling, tracking performance at different temperatures, and thermal distortion elimination tests are successfully carried out. The theoretic, simulated, and practical testing results uniformly indicate that thermal distortion can be eliminated up to 61.6% by FCM, the displacement coupling error is kept within 2.4%, and the closed-loop positioning precision is ±100 nm with 48 μm stroke. All the experimental results verify that the developed flexure nanopositioner can achieve decoupling, accurate and stable positioning targeted the ultra-precision positioning tasks under the condition of environmental temperature drift.

Index Terms—Flexure, decoupling, nanopositioner, thermal distortion, Micro/mini LED chip repairing.

I. INTRODUCTION

In the "post-Moore" era, the new generation of LED chip packaging manufacturing is stepping toward high-density, fine-pitch, and multi-array [1], [2]. The size and pitch of the latest Micro/mini LED chips are becoming much tiny (size<30 μm, pitch<10μm) [3], [4]. Unfortunately, in the process of wafer chip growth/transfer, it is inevitable to produce some dies with defections. Specifically, there are tens of millions of Micro/mini LED chips on a 75-inch display panel, where the number of defective chips is up to 10000 according to the average manufacturing yield of Micro/mini LED industry, thus the chip repairing process is a significant step [5]. As shown in Fig.1, after removing the bad points in the second step, high-precision alignment system needs to be adopted in the fourth step, which is utilized to quickly achieve the LED chip & substrate precision alignment (accuracy ≤1 μm) [6], [7]. Unfortunately, due to the environmental temperature drift, the stage will generate thermal distortion, such as warpage and depression, which will seriously affect alignment precision [8]–[11]. Therefore, how to develop a high-precision chip alignment/positioning system with thermal distortion rejection function is a challenging work for successfully achieving Micro/mini LED chip repairing.

Generally speaking, the common high-precision alignment/positioning system can be classified into the following three categories: 1) Mechanical-guided motion stages; 2) air bearing stages; 3) macro/micro composite positioning stages. For mechanical-guided motion stages, the issues such as friction, motion coupling and aging, etc., have limited its further application in the high-precision positioning system [12]–[14]. The air bearing stages are widely used in the advanced semiconductor manufacturing. However, the accuracy of air bearing stage can only be guaranteed under strictly stable environmental temperature (eg. 23°C±0.1) [15], [16]. By contrast, the macro/micro composite positioning strategy has attracted significant attention since it can realize large stroke and micro/nanometer scale precision [17]–[19]. The flexure-based nanopositioner are mainly used to further compensate the slight deviation owing to the outstanding superiorities...
including nanometer-scale resolution, no assembly, zero friction, etc. Moreover, in order to ensure the single-input and single-output motion characteristics of the stage, researchers continue to reduce the displacement coupling via symmetric structure to realize more accurate positioning control [20], [21]. Meanwhile, some relevant studies for thermal drift issues of the nanopositioners are proposed. e.g. X. Zhang et al. [22], the response model of straight circular flexure hinge under different temperature conditions by using the finite element method is established, and the effectiveness of the model is verified by experiments. W. Hou et al. [23], the generalized equations of motion for flexible linkage mechanisms, in which the thermal effects are taken into account, are developed by utilizing the virtual work method and the finite element theory. Generally, only the theoretical calculation of the thermal distortion has been taken into account in the pioneering studies, that is, the effective solution to eliminate thermal distortion of the flexure-guided nanopositioner has not been proposed in the previous literatures. Therefore, how to effectively eliminate the thermal distortion of the flexure-based nanopositioner is an urgent problem to be solved.

To cater for this requirement, a novel decoupled flexure nanopositioner with thermal distortion self-elimination property is proposed, in which three novel flexible connection modules are optimally designed to automatically reject the thermal distortion. In addition, a two-level displacement amplification and L-type decoupling mechanism are adopted to realize the high-precision positioning and displacement decoupling. Finally, a series of validation experiments are successfully implemented. The displacement coupling error between XY axis of the developed nanopositioner is verified and determined as 2.4% (within 48 µm stroke), the closed-loop positioning precision is ±100 nm, and the thermal distortion elimination rate is up to 61.6% (decreasing 4.5 µm within 7.3 µm thermal distortion at 100°C). All the results clearly validate that the developed nanopositioner with the FCM strategy can achieve thermal distortion self-elimination function. Obviously, this study presents an effective method to improve Micro/mini LED chip alignment accuracy under temperature drift.

The main contribution of this work is to develop a novel decoupled flexure nanopositioner with thermal distortion self-elimination property, which is capable of improving the alignment accuracy in the process of Micro/mini LED chip repairing. The text of this paper is organized as follows: in Section II, thermal distortion self-elimination principle and design process of nanopositioner are demonstrated; in Section III, the compliant matrix modeling and thermal deformation modeling of the nanopositioner are carried out; in Section IV, the nanopositioner is optimized and analyzed by GA and FEA methods, respectively; in Section V, a series of verification experiments and performance evaluation are presented; finally, the achievements and further work are indicated in Section VI.

II. DESIGN OF FLEXURE NANOPOSITIONER WITH THE THERMAL DISTORTION SELF-ELIMINATION

In the section, the thermal distortion elimination principle and design process are demonstrated. Through comparative analysis of several mechanisms, the displacement decoupling and amplification modules of the nanopositioner are designed, and the flexible connection modules with thermal distortion elimination are elaborately determined.

A. Thermal Distortion Self-elimination Principle with Flexure Connection

Generally, the mounting module between the flexure nanopositioning stage and fixed base is designed with rigid connection bolts. However, In the long time high temperature operation, the rigid connection constrains the free thermal expansion of the stage, and the thermal stress in the mounting module cannot be eliminated, which will result in stage thermal distortion, such as warpage or depression (see Fig. 1). Inspired by the deformation characteristics of flexure, an innovative flexible connection module (FCM) based on flexure is developed, as shown in Fig.2. Its working principle is as follows: the thermal stress from the temperature control stage or base firstly acts on the bolted joint of flexible connection mechanism, then two parallel straight beam flexures generate small displacement. Finally, the thermal stress is eliminated by the elastic deformation of flexure and does not transfer to the nanopositioner. Meanwhile, in order to keep the nanopositioner center position unchanged, three groups of FCM are installed in rotationally symmetrical method (see Fig. 2). Therefore, the deformation direction of the FCM is consistent with the connecting line between the FCM center and the nanopositioner center, which can ensure that the thermal deformation only occurs in two straight beam flexures, and does not affect the center deviation of the nanopositioner.

B. Design of Flexure Nanopositioner with Thermal Distortion Self-elimination Function

According to the above principle, FCM is designed as right and left symmetrical structure composed of two parallel straight beam flexures for higher connection strength and deformability. In addition, three FCM are arranged at optimal
angle $\theta$ and radius $r$ around the center of nanopositioner to constraint the slight parasitic displacement of parallelogram structure, which makes the thermal deformation only occur in the FCM.

Commonly, in order to meet the displacement decoupling requirements of the nanopositioner, the structure will be designed as a completely symmetrical form [24], [25]. However, the use of a completely symmetrical structure will significantly increase the overall size of the nanopositioner. Considering the size and installation position of FCM, amplification and decoupling mechanism of the nanopositioner are designed to more compact incompletely symmetrical structure. At present, the amplification mechanisms are mainly lever-type and bridge-type [26], [27]. The former displacement amplification ratio mainly depends on adjusting the distance ratio from fixed point to input and output point [see Fig. 3(a)], but which will increase the overall size significantly. By contrast, the latter depends on adjusting the angle $\alpha$ of the bridge mechanism to increase stroke, which can also reduce the overall size structure by installing the piezoelectric ceramic (PZT) inside the mechanism [see Fig. 3(b)]. Finally, we use a compound type of lever-bridge displacement amplifier (LBDA) for more compact structure and connection stability, as shown in Fig. 3(c)~(d).

Considering that the structure of the nanopositioner cannot be completely symmetrical, decoupling performance will be greatly weakened. As shown in Fig. 3(e), when the PZT generates driving force, the stiffness will imbalance due to the asymmetric structure, which results in deflection of nanopositioner and larger parasitic motion [28]. Therefore, the L-type flexure decoupling structures based on different length and thickness matching are designed to balance the stiffness at every direction, as shown in Fig. 3(f). By optimizing the structural dimensions of the four group L-type flexures, the stiffness difference is compensated. Finally, the proposed flexure nanopositioner based on flexible connection mechanism is designed (see Fig. 4).

III. MODELING OF THE THERMAL DISTORTION SELF-ELIMINATION NANOPositionER

In the section, the modeling process by complaint matrix and thermal deformation theoretical derivation is demonstrated, and the relationship between position and deformation of flexible connection modules through thermal expansion equilibrium is established.

A. Modeling of Flexible Connection Mechanism with Thermal Distortion Self-elimination

The temperature stress is caused by the change of material temperature, which will cause thermal expansion deformation [29]. The center of the flexure free endpoint is deformed by force. Thus, the relationship between force and displacement at the flexure endpoints is as follows:

$$
\begin{bmatrix}
\Delta t_{ij} \\
\Delta s_{ij} \\
\Delta \theta
\end{bmatrix}
= 
\begin{bmatrix}
c_1 & 0 & 0 \\
0 & c_2 & c_3 \\
0 & c_4 & c_5
\end{bmatrix}
\begin{bmatrix}
F_{t,ij} \\
F_{s,ij} \\
M_{ij}
\end{bmatrix}
$$
where $\Delta t_{ij}$, $\Delta s_{ij}$ and $\Delta \theta$ are the tension and compression displacement, shear displacement and rotation angle; $F_{t,ij}$, $F_{s,ij}$ and $M_{ij}$ are the tension pressure, shear force and torque, respectively; $c_i$ is the compliance coefficient of the straight beam flexure.

The deformation and compliance coefficient formula of the straight beam flexure will change slightly after temperature changes, and the flexure of FCM produces elastic deformation. Therefore, the compliance coefficients $c'$ of the straight beam flexure under thermal stress can be listed as [30]:

$$
\begin{align*}
    c'_{x,F_x} &= \frac{k l}{E(kb)(kt)} \frac{1}{kEb^3} \\
    c'_{y,F_y} &= \frac{4(kl)^3}{E(kb)(kt)} \frac{kE^b}{kEb^3} \\
    c'_{\theta,F_y} &= \frac{6(kl)^2}{E(kb)(kt)} \frac{kE^b}{kEb^3} \\
    c'_{\theta,M_x} &= \frac{12(kl)^3}{E(kb)(kt)} \frac{kE^b}{kEb^3}
\end{align*}
$$

(2)

According to the knowledge of thermodynamics, the constant $k$ can be expressed as:

$$
k = (1 + \alpha \Delta t)
$$

(3)

where $\alpha$ is the linear thermal expansion coefficient of nanopositioner, and $\Delta t$ is the variation of working temperature.

Finally, the thermal drift model is established by using the relationship of node position coordinates. There is a rigid part between the center $A_i$ of FCM and the free endpoint center $R_{ij}$ of flexure [See Fig. 2]. The expansion thermal stress occurs in this part after applying temperature load. Due to the change of position and deformation of the flexure, the constraint point $E_{ij}$ moves to $E'_{ij}$, the free point $R_{ij}$ moves to $R'_{ij}$. Where $|R_{ij}E_{ij}| = l$, $|E_2E_1| = m$, $|E_{ij}O_{ij}| = r_i$. According to the linear expansion model of solid matter, the position relations can be expressed as follows:

$$
\begin{align*}
    [x'_{E_{ij}}] &= k \begin{bmatrix} x_{R_{ij}} - x_{A_i} \\ y_{R_{ij}} - y_{A_i} \end{bmatrix} + \begin{bmatrix} x_{A_i} \\ y_{A_i} \end{bmatrix} \\
    [y'_{E_{ij}}] &= \frac{k \Delta t_{ij}}{E}\left(\begin{bmatrix} x_{E_{ij}} - x_{R_{ij}} \\ y_{E_{ij}} - y_{R_{ij}} \end{bmatrix} + \frac{\Delta \theta_{ij}}{m} \left(\begin{bmatrix} x_{E_{ij}} - x_{E_{ij}} \\ y_{E_{ij}} - y_{E_{ij}} \end{bmatrix} \right)\right)
\end{align*}
$$

(4)

(5)

After the temperature changes, the center position of flexure free endpoints relative to the center of the nanopositioner in the global coordinate can be expressed by the following thermal deformation equation:

$$
\begin{align*}
    [x'_{E_{ij}} - \Delta x] &= k \begin{bmatrix} \cos \Delta \theta \\ \sin \Delta \theta \end{bmatrix} \begin{bmatrix} x_{E_{ij}} \\ y_{E_{ij}} \end{bmatrix} \\
    [y'_{E_{ij}} - \Delta y] &= \begin{bmatrix} \cos \Delta \theta \\ \sin \Delta \theta \end{bmatrix} \begin{bmatrix} x_{E_{ij}} \\ y_{E_{ij}} \end{bmatrix}
\end{align*}
$$

(6)

where $\Delta x$, $\Delta y$ and $\Delta \theta$ are the center displacement of nanopositioner, when $\Delta \theta$ is small enough, it can be written as linear form. In order to balance the number of equations and parameters, the static equilibrium equations of nanopositioner are listed as:

$$
\sum_{i=1}^{3} \sum_{j=1}^{2} (F_{t,ij} + F_{s,ij}) = \sum_{i=1}^{3} \sum_{j=1}^{2} \left( F_{t,ij} \frac{R_{ij}E_{ij}^y}{|R_{ij}E_{ij}|} + F_{s,ij} \frac{E_{ij}E_{ij}^y}{|E_{ij}E_{ij}|} \right) = 0
$$

(7)

In conclusion, thermal distortion model of nanopositioner has been established. The position matrix parameters $x_{E_{ij}}$, $y_{E_{ij}}$, $\Delta x_{ij}$, $\Delta s_{ij}$, $F_{t,ij}$, $F_{s,ij}$ and $M_{ij}$ ($i=1,2,3; j=1,2$) are selected as unknown. It can be obtained from above linear equations, the other parameters are design sizes of the flexure nanopositioner.

B. Compliance Modeling of Amplifying and Decoupling Mechanism

The proposed nanopositioner is divided into two modules for solving the relationship between force and displacement: Magnifying mechanism and decoupling mechanism. According to the compliance theory of the straight circular flexure and compliant matrix (1), taking into account the symmetry of the mechanism and the dimension relationship in Fig.3-4, the compliant modeling of the 1/2 model is first obtained.

$$
l_{cf,t} C_i^O = T_i^1 C_R(T_i^0)^T + T_i^2 C_r(T_i^0)^T + T_i^3 C_r(T_i^0)^T + T_i^4 C_r(T_i^0)^T
$$

(9)

where $T_i^j$ is the coordinate transformation matrix from the coordinate system $i$ to $j$. $C_r$ and $C_R$ are the compliance of straight circular flexure with smaller radius and larger radius respectively, the coordinate transformation matrix is:

$$
T_i^j = P_i^j R_z(\alpha) = \begin{bmatrix} 1 & 0 & -p_y \\ 0 & 1 & p_x \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

(10)

where the rotation transformation matrix of rotating $\alpha$ around $z$ axis is $R_z(\alpha)$, and the translation transformation matrix from coordinate system $i$ to $j$ is $P_i^j$.

Since the two-stage compound displacement amplification mechanism is symmetrical, the overall compliance of the mechanism is as follows:

$$
C_A^O = [(l_{cf,t} C_i^O)^{-1} + (l_{right} C_i^O)^{-1}]^{-1}
$$

(11)

Then, considering the decoupling mechanism is consist of four groups of L-type flexures, they have different sizes for adjusting decoupling performance of the nanopositioner. Therefore, output compliance of the L-type flexures are solved respectively.

According to the coordinate system of a single L-type flexure in Fig. 4, the overall compliance of decoupling mechanism is solved as follows:

$$
C_L = T_i^2 C_l(T_i^2)^T + C_{l'}
$$

(12)

where $C_L$ is the output compliance of single L-type flexure, $C_l$ and $C_{l'}$ is the compliance of straight beam flexure in horizontal and vertical respectively, and the coordinate transformation matrix from horizontal to vertical direction is $T_i^2$.

Firstly, the output compliance $l_{cf,t-down} C_i^O$ of decoupling mechanism at the lower-left position of the nanopositioner is calculated as:
Similarly, the output compliances of the other three groups of L-type flexures are obtained as follows:

\[
\begin{align*}
\left[ \begin{array}{c}
\text{left-down} C^o_1 & \text{left-top} C^o_2 & \text{right-top} C^o_3 & \text{right-down} C^o_4 \\
\end{array} \right] = \begin{bmatrix}
P_2^o R_z \left( \frac{\pi}{2} \right) C_L & P_2^o R_z \left( \frac{\pi}{2} \right) C_L & P_2^o R_z \left( \frac{\pi}{2} \right) C_L & P_2^o R_z \left( \frac{\pi}{2} \right) C_L \\
\end{bmatrix} \begin{bmatrix}
P_2^o (R_z \left( \frac{\pi}{2} \right) C_L) & P_2^o (R_z \left( \frac{\pi}{2} \right) C_L) & P_2^o (R_z \left( \frac{\pi}{2} \right) C_L) & P_2^o (R_z \left( \frac{\pi}{2} \right) C_L) \\
\end{bmatrix}^T \\
\end{align*}
\]

Since the whole decoupling mechanism is composed of four groups of L-type flexures in parallel, the output compliance \( C^o_L \) of the decoupling mechanism is as follows:

\[
C^o_L = \left[ \begin{bmatrix}
\text{left-down} C^o_1 & \text{left-top} C^o_2 & \text{right-top} C^o_3 & \text{right-down} C^o_4 \\
\end{bmatrix} \right]^{-1} \begin{bmatrix}
\text{left-down} C^o_1 & \text{left-top} C^o_2 & \text{right-top} C^o_3 & \text{right-down} C^o_4 \\
\end{bmatrix}^{-1}
\]

So far, the compliance modeling of each basic module of the nanopositioner has been completed.

IV. MECHANISM OPTIMIZATION AND FEA ANALYSIS

As mentioned above, the performance of thermal distortion self-elimination of the flexure nanopositioner is closely related to the motion performance and geometric dimension of flexure. Therefore, the key parameters of FCM are optimized by adopting proper material and dimension with GA, and displaying FEA results with optimized parameters.

A. Material Selection

Thermal distortion self-elimination performance requires that the material of FCM has good thermal deformation ability and satisfies the fatigue strength. To cater for this requirement, the mechanical properties of several common materials of nanopositioner are listed in Table I. It can be noticed that Ti-6Al-4V and 60Si2Mn own a lower value of thermal expansion, but their density and \( \sigma_y / E \) are higher than AL7075-T6. In order to achieve light weight and larger deformation, the aluminum alloy AL7075-T6 is deemed to fabricate the proposed flexure nanopositioner.

<table>
<thead>
<tr>
<th>Material</th>
<th>E / GPa</th>
<th>Density ( \rho ) / (kg/m³)</th>
<th>Coefficient of thermal expansion/ (1/°C)</th>
<th>( \sigma_y / E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL7075-T6</td>
<td>71.7</td>
<td>2810</td>
<td>2.34×10^{-5}</td>
<td>0.00073</td>
</tr>
<tr>
<td>60Si2Mn</td>
<td>200</td>
<td>7850</td>
<td>1.15×10^{-5}</td>
<td>0.0022</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>113.8</td>
<td>4430</td>
<td>8.60×10^{-6}</td>
<td>0.0096</td>
</tr>
</tbody>
</table>

B. Optimization Statement and Results

The position dimensions of FCM are \( r_1, r_2, r_3, \theta, m \) [see Fig. 2], and structural dimensions of the flexures are \( b, l, t \) [see Fig. 4], these parameters need to be optimized for improving thermal distortion elimination performance and ensuring the position accuracy of nanopositioner. Considering the thickness and weight of the developed nanopositioner and stiffness of mechanism, we first specify \( b=20\)mm for convenient calculation. Then, the value range of \( r_1, r_2, r_3 \) is determined as \( 40\)mm ~ \( 50\)mm based on the nanopositioner size, and the range of \( m, l, t \) is determined by the results of preliminary finite element simulation analysis and machining requirement. The change of flexure nanopositioner center position and rotation angle under thermal loads can be expressed by linear displacement \( [\Delta x, \Delta y]^T \) and \( \Delta \theta \). Therefore, in order to ensure the performance of thermal distortion self-elimination, it is necessary to minimize total linear displacement \( \Delta p_{xy} \), the optimization problem described as follows.

1) Optimization objective:

\[
\min \Delta p_{xy} = \sqrt{\Delta x^2 + \Delta y^2}
\]

2) Optimization parameters: \( r_1, \theta, m, n, l, t \)

3) Constraint conditions:

a) Dimension parameters of flexure hinge: \( 40\)mm \( \leq r_1 \leq 50\)mm, \( 40\)mm \( \leq r_2 \leq 50\)mm, \( 40\)mm \( \leq r_3 \leq 50\)mm, \( 0^\circ \leq \theta \leq 20^\circ \), \( 2\)mm \( \leq m \leq 6\)mm, \( 3\)mm \( \leq l \leq 10\)mm, \( 0.3\)mm \( \leq t \leq 0.6\)mm;

b) Bending strength condition of flexure hinge: \( S_{\tau_{ij}, \text{max}} \leq \sigma_y \);

c) Condition of nanopositioner center angle under temperature load: \( \Delta \theta \leq 0.5^\circ \).

The optimization task is undertaken by the MATLAB genetic algorithm toolbox. The value of flexure dimension \( t \) and \( m \) should take into account the WEDM machining clearance, screw holes size and bearing capacity. In the process of genetic algorithm, the number of iterations is set to 50 steps. The optimal size of the nanopositioner is shown in Table II.

<table>
<thead>
<tr>
<th>Optimized parameters</th>
<th>Value range</th>
<th>Initial value</th>
<th>Optimal solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_1 )</td>
<td>[40, 50]</td>
<td>40</td>
<td>45.64mm</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>[40, 50]</td>
<td>40</td>
<td>45.00mm</td>
</tr>
<tr>
<td>( r_3 )</td>
<td>[40, 50]</td>
<td>40</td>
<td>45.76mm</td>
</tr>
<tr>
<td>( \theta )</td>
<td>[0, 20]</td>
<td>10^\circ</td>
<td>15^\circ</td>
</tr>
<tr>
<td>( m )</td>
<td>[2, 6]</td>
<td>3</td>
<td>4.92mm</td>
</tr>
<tr>
<td>( l )</td>
<td>[3, 10]</td>
<td>5</td>
<td>5.14mm</td>
</tr>
<tr>
<td>( t )</td>
<td>[0.3, 0.6]</td>
<td>0.35</td>
<td>0.40mm</td>
</tr>
</tbody>
</table>

C. Finite Element Analysis and Evaluation

ANSYS Workbench 15.0 is used to carry out deformation, modal and thermal stress analysis of the nanopositioner, the analysis process and results are as follows. When the initial simulation temperature is set at 22°C, the temperature loads on the base of the nanopositioner are 25°C, 60°C and 100°C, respectively. The comparative analysis schemes of the two connection methods are as follows:

1) Without FCM: According to the traditional rigid installation method, the nanopositioner is fixed directly by four rigid bolts on the edge of the base.
2) With FCM: According to the proposed FCM installation method, the nanopositioner is fixed on the base by three bolts in the form of flexure connection. And then, the finite element simulation is carried out.
Because the thermal stress from the base is constrained by rigid bolts connection, the nanopositioner without FCM appears warping and initial position deviation[see Fig. 5(b)]. Meanwhile, the rotation coupling analysis is shown in the Fig. 4(a) and (e), the temperature field result of nanopositioner without FCM indicates that nanopositioner is exposed to higher temperatures and thermal stress[see Fig. 5(c),(d)]. In contrast, the thermal distortion has been effectively reduced by 64%[see Fig. 5(b),(f)], because thermal transmission process from the base to nanopositioner is absorbed by the flexures of FCM, and thermal stress of the nanopositioner is focused on the FCM[see Fig. 5(f)].

In addition, the flexure nanopositioner mainly moves along x and y direction under actuation of PZT, the modal analysis is shown in Fig. 6. The results show that the stiffness of x-axis and y-axis of the proposed stage is considerably consistent, and the first two order resonance frequencies are very close (566.5Hz and 606.8Hz).

V. EXPERIMENTS AND DISCUSSION

In this section, the prototype system is established. In order to successfully implement the experiments, the temperature controlled device and heat insulation box are built and tested firstly. Then, the high precision sensor is accurately installed. Finally, a series of experimental tests including open-loop and closed-loop performance tests, thermal coupling tests are carried out.

A. Establishment of Prototype System

The experimental system is displayed in Fig. 7, including a laser displacement sensor (PS-CTRL-V1.4-TAB) and a set of PTC temperature control system. AL7075-T651 material is fabricated the prototype via the WEDM. Two PZT actuators (XMTPSt150/5×5/20L) actuate the nanopositioner, a three-channel voltage amplifier (E.03, XMT) is used to output suitable voltage. The control implementation of this experimental system is achieved by using the dSPACE rapid prototyping simulating system (DS-1007, dSPACE). In order to avoid external vibration caused by various kinds of environmental disturbances, all instruments are placed on the vibration isolation stage (WN01AL, Winner optics).

B. Performance Validation Tests of Nanopositioner

1) Performance Calibration of Temperature Control System: Before implementing thermal distortion resistance performance experiment, due to the hysteresis and heat loss of the heating system, the heating performance and temperature holding error must be verified to calibrate the temperature control system. In addition, it is necessary to eliminate the influence of temperature change on the sensor accuracy as much as possible. Therefore, the system is placed in a relatively insulated temperature box, and the laser head of the laser interferometer is placed outside of the box. Meanwhile, the PTC heating device is installed under the base plate of...
the nanopositioner, which can most accurately simulate the heating methods of chip repairing process. As shown in Fig. 8, the experiment system takes about 20 min to raise the workspace temperature from room temperature (about 26°C) to 60°C, and the temperature holding error is less than 2°C, when the system temperature is stable, the disturbance of the sensor is kept within 300nm.

Fig. 8. Temperature and measurement noise in experiment system.

2) Modal and Decoupling Tests: It is necessary to verify decoupling performance, modal and motion precision firstly for testing the dynamic performance of the nanopositioner. The dynamic response test is realized by inputting sweep signal, sine wave and stair signal, and output results are measured by laser interferometer, and the time domain sweep results are transformed into frequency domain signal by Fourier transform. As shown in Fig. 9(a), where \( f_1 \) is 556.87Hz, \( f_2 \) is 579.32Hz. Compared with FEA simulation results, the experimental value is close to theoretical value. Besides, the output displacement coupling error of the nanopositioner is tested for verifying the validity of designed L-type decoupling mechanism. And the parasitic displacement of another axis is measured by inputting the maximum allowable voltage (100V output by voltage amplifier) of PZT actuation, as shown in Fig. 9(b), (d). The displacement coupling error is 2.4% (full stroke 48 \( \mu \)m). Finally, the closed-loop motion precision tests of nanopositioner are shown in Fig. 9(c), it has positioning precision of 100nm. All test results indicate that the performance of developed nanopositioner satisfies the requirements.

3) Tests of Thermal Distortion Self-elimination: In order to verify the performance of the proposed nanopositioner under wide-range temperature drift, a series of open-loop comparative tracking experiments are carried out at different temperatures (25°C, 40°C, 60°C), including sine wave, triangular wave (with FCM and without FCM), as shown in Fig. 10. Affected by the increase of temperature, the tracking curve of stage without FCM generates larger phase lag and amplitude attenuation. By contrast, the developed nanopositioner with FCM can still keep good tracking property, and it can basically resist the influence of wide-range temperature drift.

For better validation of thermal distortion self-elimination performance of the developed FCM, three regularly distributed points on the upper surface of the nanopositioner are selected as the deformation measurement points by using the traditional flatness measurement scheme. The thermal distortion comparative tests of nanopositioner at high temperature (100°C) are carried out, as shown in Fig. 11. Obviously, the traditional stage with rigid connector has about 7.3 \( \mu \)m deformation value relative to central point, which induces serious warpage of stage. By contrast, the nanopositioner with FCM only generates about 2.8 \( \mu \)m uniform deformation at three point, these slight deformation comes from the z-direction expansion of the fixed base. Obviously, most of the thermal distortion is absorbed by FCM.

Fig. 9. Modal, decoupling performance and closed-loop motion precision test results of the proposed nanopositioner.

Fig. 10. Open-loop trajectory tracking experimental results at different temperatures with FCM and without FCM.

Fig. 11. Comparison of thermal warpage effect of nanopositioner with FCM and without FCM.

In addition, collecting the deformation of the upper surface repeatedly through laser interferometer, three-dimensional deformation surface is obtained. Meanwhile, the industrial camera is adopted to capture the deformation of the nanopositioner.
and FCM at different temperatures, as shown in Fig. 11-12. It can be validated from these results, by utilizing the deformation of flexures, the proposed FCM eliminates the warpage of stage caused by the thermal expansion deformation of the fixed base.

C. Performance Evaluation and Discussion

In high-precision chip repairing processes, the influence of temperature drift will greatly affect alignment precision. In this work, a thermal distortion self-elimination nanopositioner based on flexible connection mechanism is developed. The displacement coupling error of the proposed nanopositioner is 2.4% (full stroke is 48 μm), and the closed-loop positioning precision is ±100 nm. The surface deformation results demonstrate that the thermal deformation of the stage without FCM is 7.3 μm at 100°C, but the developed nanopositioner with FCM is only 2.8 μm (reduced by 61.6%), which is close to the theoretic and FEA evaluation results (64%).

In a word, a series of comparative temperature experiments of tracking and deformation consistently confirm that FCM can effectively eliminate the influence of thermal warpage and ensure precision of the chip repairing. In further work, the thermal distortion self-elimination performance of the developed stage can be further enhanced by employing topology and module optimization theories [31].

Fig. 12. Thermal distortion elimination performance of proposed nanopositioner in LED repairing operation. (a)-(c) thermal distortion of stage without FCM; (d)-(f) thermal distortion elimination principle of FCM; (g)-(i) the proposed nanopositioner performance.

VI. CONCLUSIONS

An asymmetric structural flexure nanopositioner with thermal distortion self-elimination function is proposed and validated in this work. The main achievements are concluded as follows: 1) A novel decoupled flexure nanopositioner with three flexible connection modules is designed, optimized and fabricated, which aims to reduce the influence of temperature drift on chip accurate alignment/positioning; 2) Theoretical analysis including thermal deformation relationship derivation and whole mechanism compliance modeling are carried out, and the FCM is optimized by the genetic optimization algorithm (GA) and FEA evaluations; 3) A series of validation experiments are successfully carried out in detail, the displacement coupling error is 2.4% under 48 μm stroke, the closed-loop positioning precision is ±100 nm with 48 μm stroke, and thermal distortion at Z axis is eliminated to 61.6%. All the experimental results verify that the developed flexure nanopositioner can achieve decoupling, accurate and stable positioning targeted the ultra-precision positioning tasks under the condition of environmental temperature drift.

In future work, the flexure nanopositioner mechanism should be further optimized, and the advanced nanopositioning control strategy should be investigated for achieving more efficient Micro/mini LED repairing process.

REFERENCES


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