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Finite Element Analysis for Connection Mechanism in Macro-Micro Platform

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***Abstract*—Connection mechanism is a key component in macro-micro platform which can achieve high acceleration, ultra-high precision positioning and a long stroke. The paper presents a connection mechanism combining with a voice coil motor (VCM) and a piezoelectric stack actuator (PSA). The connection mechanism was investigated by mechanical analysis, related property indices, and some preliminary studies were as following: in the beginning, static analyses in multi-cases were carried out to ensure a solid foundation for the connection mechanism. The maximum deformation and stress were obtained for a validation evidence of structural reliability. Stress and deformation distribution were disclosed, and the relevant change trends of the maximum stress and deformation in multi-cases were obtained. However, the connection mechanism is employed to realize high acceleration, while to achieve ultra-high precision positioning. Since resonance between connection mechanism and other bodies must be avoided. It is convenient and economic to do modal analysis by ANSYS, and then the intrinsic frequency of connection mechanism will be obtained. The results indicate the connection mechanism has a higher resonance frequency than others. Though there are realization of the solid foundation and avoiding resonance, some environmental factors have hindered ultra-high precision positioning such as the relative air humidity, temperature and so on. Since the temperature up to 100℃ from heating problem of VCM inevitably produces a great deal of heat energy which can bring thermal deformation and stress, it is obliged to explore thermal deformation and stress distribution of connection mechanism by thermal-structure characteristic analysis. Thermal deformation and stress change trends under different temperature loads are revealed, which will provide a support for ultra-high precision. It is expected that finite element simulation can be an effective tool to realize the design of ultra-high precision connection mechanism in high acceleration positioning.**

***Index Terms*—ultra-high precision, connection mechanism, high acceleration positioning**

I. INTRODUCTION

In the fields of high-speed sample pipetting of biological engineering, precision positioning of robot, microelectronics manufacturing application such as lithography machine or SMT(Surface Mounted Technology), a device needs to make a reciprocating positioning motion in start and stop frequently state for the precise positioning which must be high speed, high acceleration, ultra-high precision position and a long stroke [1]-[3]. Traditionally, a VCM as direct transmission is widely employed to obtain precise positioning motion [4]. Though the demands of high speed, high acceleration and a long stroke is met, its precision positioning is only at a micron level, which cannot satisfy ever-increasing accurate positioning requirements to improve productivity [5]-[7]. Moreover, VCM still has significant bandwidth limitations (<100Hz) which have hindered the further improvement of microelectronics manufacturing performance [1]. Therefore, a connection mechanism is brought forward [8]-[13]. In the connection mechanism, VCM as macro actuator can realize high speed in a long stroke and PSA as micro actuator can achieve a nano-positioning motion. The bandwidth limitations of VCM will also be greatly improved by PSA. At last, high speed, ultra-high precision position and a long stroke will be realized by the each other compensation between VCM and PSA. Many studies presented the macro-micro system [14]-[17]. A connection mechanism combining with a PSA and a VCM was proposed, and the dynamic positioning parameters were studied by the nonlinear, double-dynamic Taguchi method, it was experimentally demonstrated that the method was suitable for precision positioning devices using the hybrid actuators [14]. A connection mechanism system covering a ballscrew and a piezoelectric nut was developed. Its positioning error could be fine-adjusted to the nanometer level and the motion stability at low speed could be improved by the piezoelectric nut mechanism [15]. A connection mechanism integrated two types of motion reported: a macro motion driven by DC servomotor for large workspace and a micro motion driven by PZT actuator for high precision. Some related design parameters were identified and the optimal levels for the design parameters were determined [16]. A connection mechanism consisting of four Halbach linear active magnetic bearings and four VCMs was described. It was obtained ±1 nm

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mean tracking error and 4.7 nm jitter at the scan with 10 mm/s constant velocity [17].

Although many researches on connection mechanism have been reported, the systematic study on connection mechanism is still very little. In the paper, connection mechanism is investigated by mechanical analysis, related performance indices and some preliminary studies. This article is organized as follows: Section II describes the structural composition of connection mechanism. Static analyses of connection mechanism in six cases are discussed in Section III. Modal analysis and thermal structure coupled analysis are investigated in Section IV and Section V respectively. Finally, conclusions are summarized in Section VI.

II. MODEL STRUCTURE

The connection mechanism is employed to simultaneously satisfy all ever-increasing performance demands. That is, VCM is employed to provide a linear motion with a long stroke, high speed. PSA can be driven to compensate a micron error of VCM and continue travelling to a predetermined nano-positioning. Therefore, the connection mechanism is able to realize accurate positioning. The property indices of the connection mechanism in the design are listed as following: the stroke is 80 mm, the maximum acceleration is 150 m/s^2, the maximum speed is more than 1 m/s, the accuracy is 10 nm and the equivalent mass is 3 kg. According to the indices, a structural model is preliminarily built up, it contains VCM, connection frame, PSA and platform, as shown in Fig. 1.

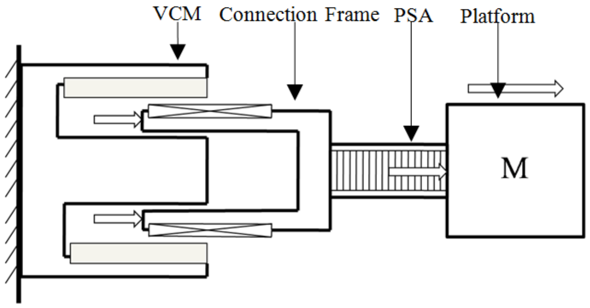


Figure 1. The model structure of platform

VCM drives the connection mechanism to realize a long stroke and high speed motion because of its superior characteristic such as high acceleration, high speed, fast response, no-lag, infinite resolution, etc. Furthermore, VCM, as a direct transmission applied in connection mechanism, makes a great effect on noise reduction, mechanism simplified, easy-maintenance and so on. According to the indexes of the connection mechanism in the design, a rectangular structure is adopted in VCM, the load is set as 3 Kg, the maximum velocity and acceleration performance parameters are set as 3 m/s and 150 m/s^2 respectively.

Ultra-high precision positioning can be achieved mainly by the PSA. PSA compensates for the error of a long stroke driven by VCM and then continues driving platform to realize the nano-positioning. In a whole travel, the PSA and platform are driven by VCM for reciprocating motion which has high speed and acceleration. However, the PSA will inevitably be pushed and pulled in the reciprocating motion. When PSA is at the maximum acceleration, the maximum pull of PSA is obtained, as shown in Fig. 2. PSA has to bear great pressure, however, its tensile force F_p is limited. On the basis of the performance indices of connection mechanism, the maximum tension force F_p must satisfy the expression as following:

$$F_P > F_{pmax} = Ma = 3\times 150 = 450\ (\mathrm{N}) \qquad (1)$$

where F_p is the tensile pull force of PSA, F_{pmax} is the maximum pull force of PSA, M is the equivalent mass of connection mechanism, and a is the maximum acceleration.

According to the maximum pull force of PSA, P-845.20 from PI Company of German is a prefer choice, as shown in Fig. 3. The tensile pull force of the actuator F_P is 700(N) which is greater than the maximum pull force F_{pmax}. The closed-loop stroke is 30 um. The resonant frequency is 12 KHz. All these satisfy the design requirements and related property parameters are shown in Table I.

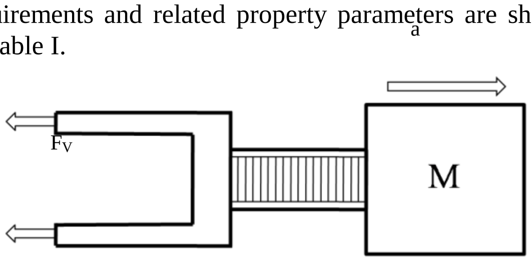


Figure 2. Force analysis of macro-driven

Figure 3. Piezoelectric model as P-845.20 from PI

TABLE I. PROPERTY INDICES OF P-845.20.

Push /pull (N)	Closed-loop stroke (um)	Closed-loop resolution (nm)	Frequency (KHz)
3000/700	30	0.6	12

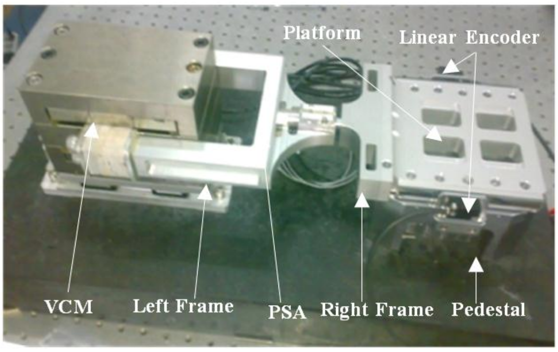


Figure 4. Connection mechanism in macro-micro platform

The connection mechanism composed of VCM, left frame, PSA, right frame and platform is built up, as shown in Fig. 4. The motion positioning of platform can be measured by linear encoder for positioning feedback. And high speed, high acceleration, ultra-high precision positioning and a long stroke will be realized by the connection mechanism.

III. STATIC ANALYSIS

In the actual driving process, connection mechanism starts and stop circularly to obtain a scheduled position and the scheduled position covering a long stroke, the maximum acceleration and speed will be realized. That is, connection mechanism must reach the preset speed by the driving of VCM to positive micro-positioning, and then VCM stops driving. After that, if precision positioning error is met, error compensation and nano-positioning will be achieved by PSA. Conversely, connection mechanism will not stop until meeting precision positioning error. Detailed operation processes are described as follows:

In case 1, connection mechanism is driven by VCM from initial static state to the maximum speed. Meanwhile, it is affected by friction force between platform and pedestal. As a result of synthetic action from driving and friction force, it will product inevitable deformation and stress in connection mechanism. In order to study whether the connection mechanism has sufficient structure stability, friction force will be enlarged to infinity, that is, the right end of platform will be constrained completely. In this way, the boundary condition of case 1 is equivalent to: the end planes of arms are driven by the driving force F_V of VCM, and the right end plane of platform is completely constrained, as shown in Fig. 5(a). However, the maximum acceleration 150 m/s^2 must be obtained, so the enough drive force has to be provided. By Newton's second law, the drive force can be expressed as:

$$F_V = F_{pmax} = Ma = 3\times150 = 450 \text{ (N)} \qquad (2)$$

In case 2, connection mechanism does decelerating motion by reverse drive force during the process from the maximum speed position to micro grade positioning. Because of inertia effect, the positive deformation and stress of connection mechanism is inescapable. To be able to efficiently and conveniently research on the deformation and stress, the end plane of arms is constrained while the connection mechanism is affected by the maximum acceleration. Consequently, the boundary condition of case 2 is equivalent to: the end planes of arms are constrained and the connection mechanism is affected by acceleration effect, the maximum acceleration is 150m/s^2, as shown in Fig. 5(b).

In case 3, under the condition of satisfying positioning accuracy error, the connection mechanism is driven by the push force F_P from inverse piezoelectric effect of PSA. The pull resistance of PSA as applied load is 700N. And then, the boundary condition of case 2 is equivalent to: the end planes of arms are constrained and the surface loaded between frame and PSA is applied, as shown in Fig. 5(c).

On account of circularly start-stop motion, some other modes of motion includes case 4, case 5 and case 6, as shown in Fig. 5(d), Fig. 5(e) and Fig. 5(f) separately. Moreover, the modes of motion in case4, case 5 and case 6 are respectively exact reverse of case 1, case 2 and case 3 except numerical equal. Therefore, their corresponding loads are equal and opposite in direction. The boundary conditions of six cases are shown in Table II.

According to the above conditions, the 3D model of the connection mechanism built in Solid Works was directly imported into ANSYS12.1 and the model consists of left frame, piezoelectric stack actuator, right frame and platform. Their relevant material properties, element types are shown in Table III. Finite element model of the connection mechanism was analyzed to obtain the deformations and stress distribution and their changing trends under different loads in each case. Some important results are obtained as following:

For case 1, connection mechanism is driven by VCM. The maximum deformation is 33.5 μm which symmetrically appears on the end planes of arms, as shown in Fig. 6(a). The maximum stress is 12.5MPa which appears on the surface between PSA and platform, as shown in Fig. 6(b). The maximum stress is far less than the yield strength as 469 MPa [18]. So the connection mechanism is safe and reliable. Under the same situation, the changing trends of deformation and stress distribution of connection mechanism can be obtained by changing the surface loads. The result is shown in Fig. 6(c). It is easily to find that the maximum deformation and stress increase with the loads.

For case 2, the connection mechanism is affected by the positive acceleration. And the case 3 is at the beginning of being driven by PSA. Their changing trends of deformation and stress distribution of connection mechanism can be obtained by changing loads, as shown in Fig. 7 and Fig. 8 separately. It is easily to find that the maximum deformation and stress increase with loads.

The boundary conditions of case 4, case 5 and case 6 are the same as case 1, case 2 and case 3 in opposite directions. The maximum deformation and stress of every case is shown in Table IV. The maximum deformation in all cases is in case 2 and case 5 because of effect of the highest acceleration. The maximum stress in all cases is in case 3 and case 6 as a result of the small contact area between PSA and platform. However, the changing trends of the maximum deformation and stress increase with loads under different loads in six cases.

TABLE II. BOUNDARY CONDITIONS IN MULTI-CASES.

Cases		Case1	Case2	Case3	Case4	Case5	Case6
Boundary conditions	Load	450N	150m/s^2	700N	-450N	-150 m/s^2	-700N
	Position	End plane of arms	Connection mechanism	Contact surface	The same as case1	The same as case2	The same as case3
	Constrained position	Right end of platform	End planes of arms	End planes of arms	The same as case1	The same as case2	The same as case3

TABLE III. THE MATERIAL PROPERTIES, THE REFERENCE VALUE OF THE COMPONENT IN SYSTEM.

Component	Material	Element type	Elasticity ($\times10^{10}$Pa)	Poisson ratio	Density ($\times10^3$kg/m^3)	Thermal conductivity (W/m·℃)	Thermal expansion coefficient ($\times10^{-6}$℃$^{-1}$)	Air convection coefficient W/(m^2·℃)
Left Frame	AL_2O_3	SOLID92	7.2	0.33	2810	130	2.36	20
PSA	Piezoelectric	SOLID92	2.2	0.22	2300	1.49	1.08	20
Right Frame	AL_2O_3	SOLID92	7.2	0.33	2810	130	2.36	20
Platform	AL_2O_3	SOLID92	7.2	0.33	2810	130	2.36	20

TABLE IV. THE MAXIMUM DEFORMATION AND STRESS IN MULTI-CASES

Cases	Case1	Case2	Case3	Case4	Case5	Case6
The maximum deformation (μm)	33.5	46.9	38.1	33.5	46.9	38.1
The maximum stress (MPa)	12.5	12.9	14.2	12.5	12.9	14.2
The position of the maximum deformation	Symmetrically on the end planes of arms	Right end plane of platform	Right end plane of platform	Symmetrically on the end planes of arms	Right end plane of platform	Right end plane of platform
The position of the maximum stress	Surface between PSA and platform	Surface between PSA and platform	Surface between PSA and platform	Surface between PSA and platform	Surface between PSA and platform	Surface between PSA and platform

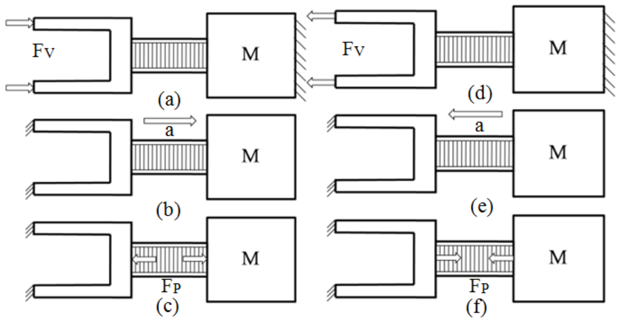
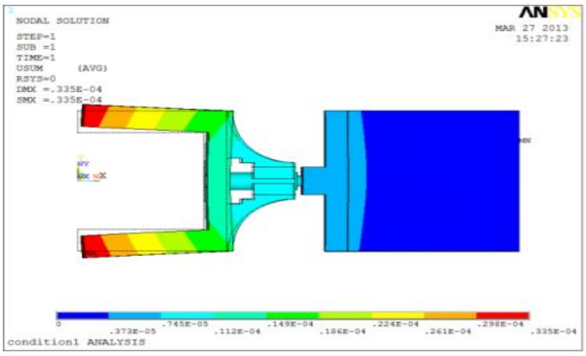
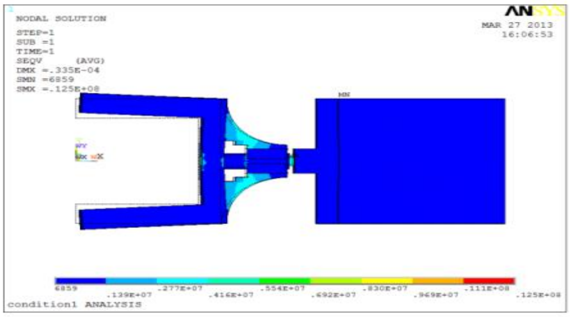


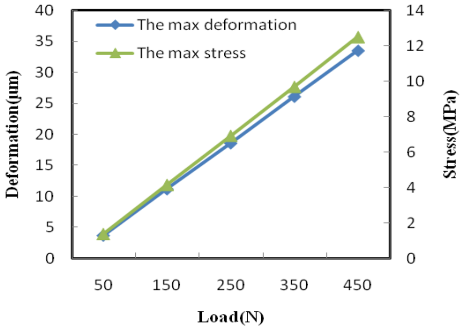
Figure 5. Force analysis in different cases.



(a)



(b)



(c)

Figure 6. Static analysis of case 1. (a) Deformation distribution. (b) Stress distribution. (c) The maximum deformation and stress under different loads.

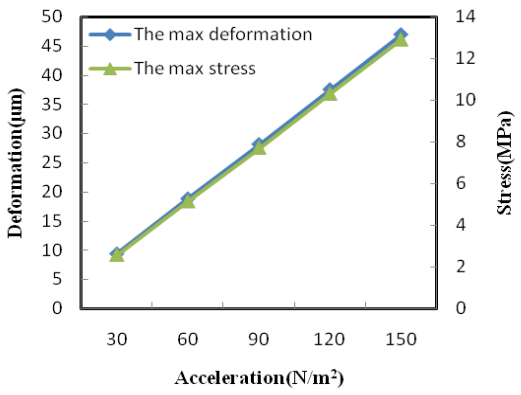


Figure 7. The maximum deformation and stress of different loads in case 2.

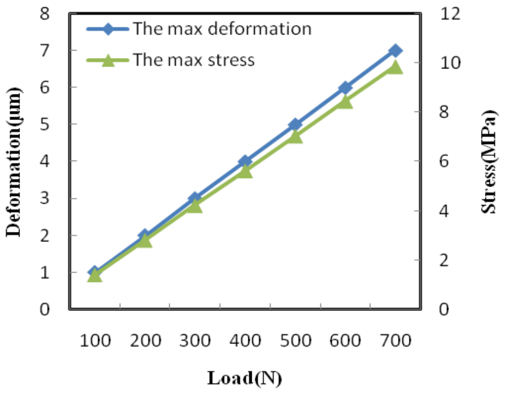


Figure 8. The maximum deformation and stress of different loads in case 3.

TABLE V. FREQUENCIES AND MODE SHAPES IN MULTI-CASES

Order	The 1st	The 2nd	The 3th	The 4th	The 5th	The 6th
Frequency (Hz)	1486	1811	2041	3689	5243.	5456
Mode shape	Upward along Z direction	Swing along X direction	Twist along X direction	Extruding along Z direction	Shifting along X direction	Downward swing along Z direction

IV. MODAL ANALYSIS

In the high-speed motion of connection mechanism, the natural frequencies and the vibration modes must be considered and controlled to avoid the resonance with the machine body. The first order mode has been obtained by the finite element model calculation. The primary frequency is 1491.3 Hz, as shown in Fig. 9, that is, the natural frequency is much higher than the driven frequency of the VCM, which can avoid resonance with connection mechanism. Table V shows the frequencies and vibration model of the first six order modes.

Figure 9. First order mode shape.

V. THERMAL-STRUCTURE ANALYSIS

In connection mechanism, ultra-high precision positioning has been influenced directly by thermal deformation which comes from temperature rise of voice coil motor. Temperature distributions, thermal deformation and stress of connection mechanism have been calculated by finite element method.

Since the temperature up to 100℃ from heating problem of voice coil motor inevitably produces a great deal of heat energy which can bring thermal deformation and stress, it is necessary to explore thermal deformation and stress distribution of connection mechanism by thermal-structure characteristic analysis. Thermal-structure analysis was studied in environment whose temperature could be set to 20℃ and thermal loads was applied on the end planes of arms. The reference values of material properties, element types are shown in Table III.

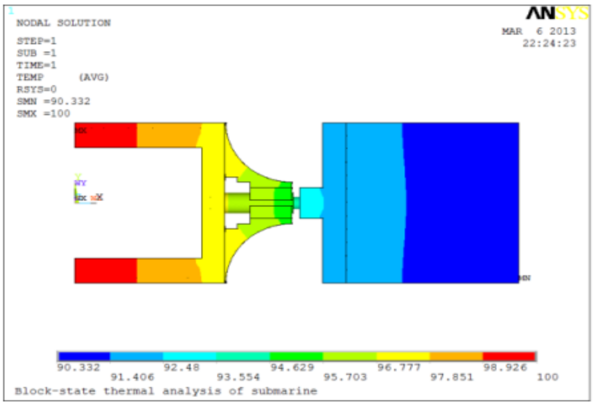


Figure 10. Temperature distribution of connection mechanism

At first, the temperature distribution of connection mechanism needs to be obtained before thermal-structure analysis. Hence, temperature distribution of macro-micro is gotten by finite element method, and the highest and lowest temperature are 100 ℃ and 90.3 ℃, appear on the end arms and the right end platform around, as shown in Fig. 10. Under the same condition, the changing trend of temperature increases with different temperatures, as shown in Fig. 11.

And then, thermal deformation and stress distribution of connection mechanism are also obtained by finite element method. The maximum thermal deformation is 717 μm which appears on the right end planes of platform and the maximum stress is 348 MPa which are on the end planes of arms, as shown in Fig. 12(a) and Fig. 12(b) respectively. The maximum thermal stress is far less than the yield strength as 469 MPa [18]. So the connection mechanism is safe and reliable. In the same way, the changing trends of thermal deformation and stress increase with temperature under different temperatures, as shown in Fig. 13.

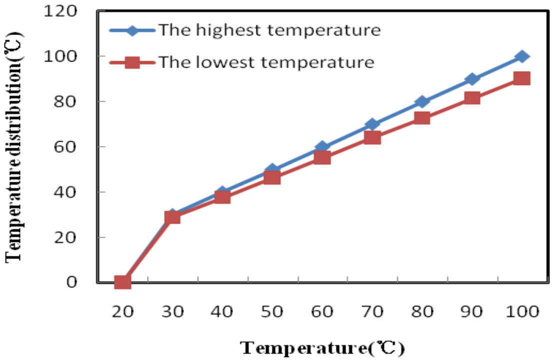
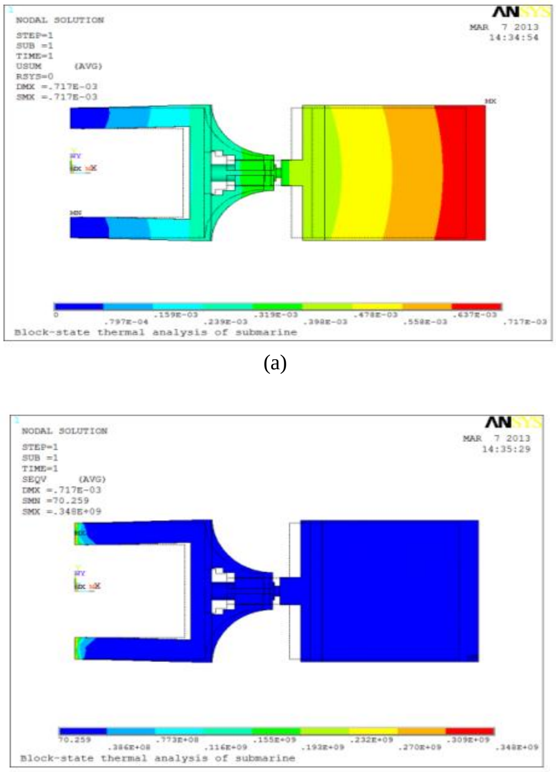


Figure 11. The temperature of connection mechanism under different temperatures



(a)

(b)

Figure 12. Thermal-structure analysis of connection mechanism. (a) Thermal deformation distribution. (b) Thermal stress distribution.

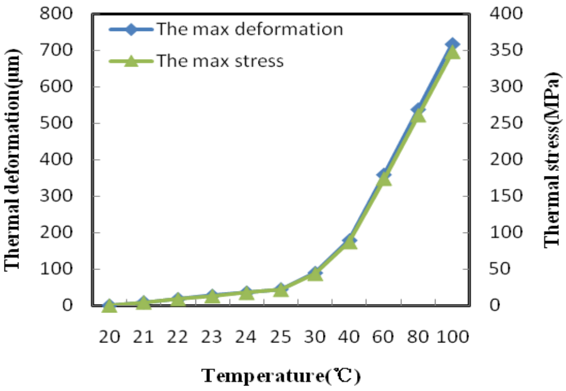


Figure 13. The maximum deformation and stress under different temperatures.

VI. CONCLUSION

In this research, we have developed an ultra-high precision connection mechanism in high acceleration positioning. The connection mechanism was investigated. Some important conclusions are obtained as following: (1) static analyses of connection mechanism in six cases are discussed. The maximum deformation among all cases is 46.9 μm in case 2 and case 5 as a result of effect of the highest acceleration. The maximum stress among all cases is 14.2 MPa in case 3 and case 6 because of the small contact area between PSA and platform. However, the connection mechanism is safe and reliable. From this, it is concluded that connection mechanism is safe and reliable. Moreover, the changing trends of the maximum deformation and stress increase with loads under different loads in six cases. (2) The primary frequency of connection mechanism is 1491.3 Hz, that is, the natural frequency is much higher than the driven frequency of the VCM, which can avoid resonance with VCM. The results of static analysis and modal analysis provide a theoretical foundation for the real connection mechanism application. (3) The maximum thermal deformation is 717 μm which appears on the right end planes of platform and the maximum stress is 348 MPa which are on the end planes of arms. The connection mechanism is also safe and reliable. In the same way, the changing trends of thermal deformation and stress increase with under different temperatures. Finally, it is expected that finite element simulation can be an effective tool to realize the design of ultra-high precision connection mechanism in high acceleration positioning.

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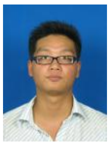

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