Advances in Engineering Research, volume 123
2nd International Conference on Materials Science, Machinery and Energy Engineering (MSMEE 2017)

Design and Optimization of A Novel Micro-step Rotary Actuator Worktable

Xiaozhou Zheng[a] and Xue Wang[b]

Academy of Armored Forces Engineering,Beijing 100072,China

[a]hfutzxz@163.com,[b]hfutwx@163.com

Abstract: A novel micro-step rotary actuator worktable is presented in this paper.The worktable uses the symmetric structure design and works with an inside clamping of the stator, controlling the axial positioning of the motion conversion mechanism and reducing the deformation of deviation of the axial at the same time.The motion conversion mechanism is based on the principle of screw transmission,adopting the structure of the uniformly distributed thin flexible hinge at the axial to eliminate the gap of the axial connection.The worktable uses the symmetric design,having the advantages of with miniaturization, easy fabrication and installation.According to calculation and finite element analysis, we can find that the linear relationship between the output angular and axial displacement of the motion converting mechanism.The important factors affecting the drive structure are analyzed by the method of extreme difference analysis, the optimal value is determined and its structure is optimized.

Keywords: Micro-step rotary actuator worktable;Flexible hinge;Clamp; Design;Optimization

1.Introduction

Miniaturization is one of the important development directions of current automatic control system.The micro-electro-mechanical system and micro-nano-technology, which emerged in the 1980s, opened up a new situation for the miniaturization of the automatic control system and pointed out a new and effective way for the miniaturization of the actuators.Micro-positioning technology is an important part of modern manufacturing technology, and it is also one of the key technologies of nanotechnology in 21st Century[1].Piezoelectric ceramic actuator is widely applied in the field of nano precision positioning,with the advantages of low heat, large capacity, high resolution and simple structure.

The micro-step rotary actuator worktable transforms the micro displacement of the actuator caused by the piezoelectric ceramics into the angle output,based on the principle of screw transmission and combined with the flexible hinge[2].The design materializes the structure of the worktable,and adopts the structure of both ends of the top clamping structure to realize the axial positioning of the middle movement conversion mechanism.The axial flexible hinge structure is adopted to make the motion conversion mechanism eliminate the axial displacement while transmitting torque.The worktable uses the symmetric design,having the advantages of miniaturization, easy fabrication and installation.

2.Principle of Micro-step Rotary Actuator Worktable

Micro-step rotary actuator worktable is based on the principle of screw transmission,in order to achieve the continuous rotary motion of the output shaft.The step motion is based on the alternating action of the clamp.The coordination process of clamping and driving is achieved by the way of clamping - rotation - clamping.The principle of micro-step rotary actuator worktable is shown in Fig. 1.

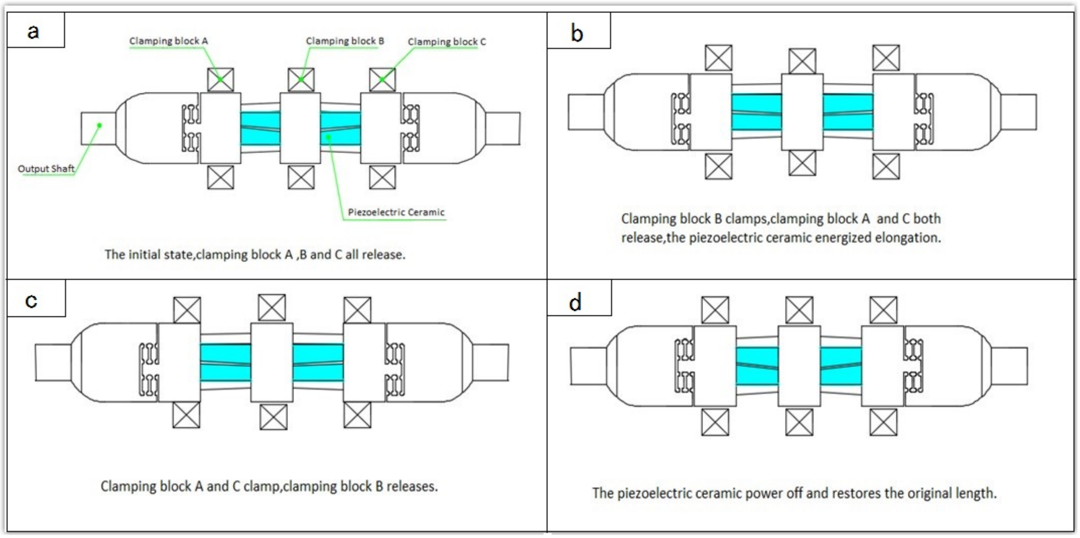


Fig.1 Principle of Micro-step Rotary Actuator Worktable

The motion conversion process of the worktable mainly consists of the following three steps:
1)The climping process;
2)The driving process of piezoelectric ceramic actuator;
3)The alternate action process of clamping block and actuator.

The initial state is shown in Fig.1(a),the motion transformation mechanism in a free state, clamping block A ,B and C all release.Driving process of piezoelectric ceramic actuator is shown in Fig.1(b),clamping block B clamps,clamping block A and C both release,the piezoelectric ceramic energized elongation，makes A and C rotate an angle at the same time by screw transmission.The alternate action process of clamping block and actuator is shown in Fig.1(c),clamping block A and C clamp,clamping block B releases.Finally,the piezoelectric ceramic actuator is powered off, and the motion conversion mechanism restores the original length as shown in Fig.1(d).One action cycle of the counterclockwise output angle of the actuator completes by the above process. Repeating the above steps, the actuator can realize the counterclockwise continuous rotation.On the contrary, changing the clamping action sequence can realize the clockwise continuous rotation.

3.Structure design of micro-step rotary actuator worktable

3.1 Overall structural design

The basic structure of micro-step rotary actuator worktable is shown in Fig.2,mainly composing of connecting bolts, a top and a bottom base, a shaft end positioning device and a motion conversion system.The base of the table adopts symmetrical shaft end spherical positioning device on both sides,in the realization of the axial positioning of the movement mechanism at the same time not affecting the rotation output.

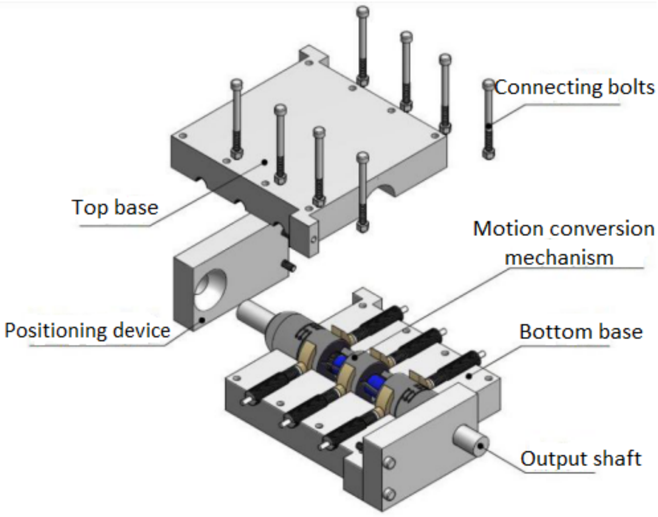


Fig.2 Exploded Diagram of Micro-step Rotary Actuator Worktable

3.2 Design of motion conversion mechanism

The motion conversion mechanism consists of A, B, C three sections， where section A and C are same and symmetrical about section B.Section B and A are connected by three identical rectangular spiral spring sheets， section B and C are the same.The rectangular spiral spring sheets are evenly distributed on the circumference,the helix angle is β, the pitch is h, and the radius is R.Section A and C are connected with the output shaft through the screw thread.The two sections are designed with a flexible hinge to transmit torque and eliminate axial clearance.

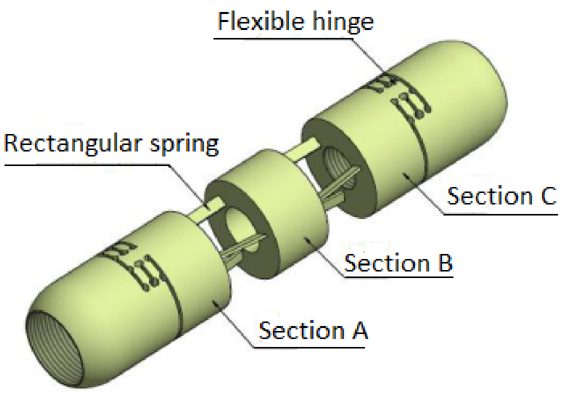
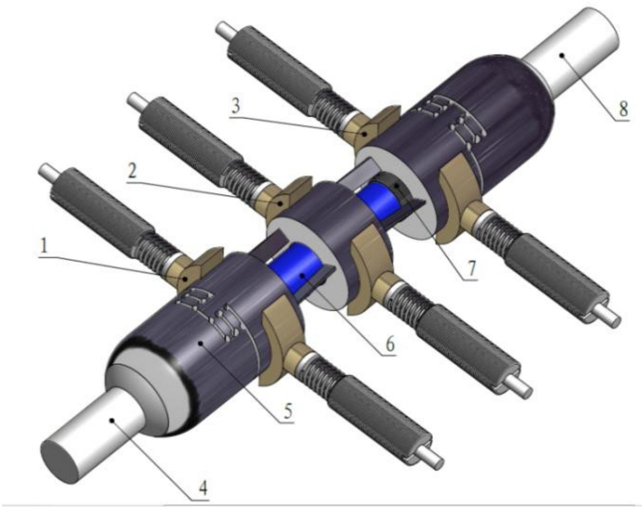


Fig.3 Design of Actuator Structure

The piezoelectric ceramic is installed inside the motion conversion mechanism,both ends are connected by screws with motion conversion mechanisms section A or C,and preloaded.The micro displacement generated by piezoelectric ceramics is converted into the output angular displacement by the motion conversion mechanism.The angular displacement is transmitted to the output shaft 1 and 2 by flexible hinges.Through the corresponding clamping block of the alternating clamp and recovery, continuous output angle is achieved[3].The assembly relationship of actuator is shown in Fig.4.



1. Section A 2. Section B 3.Section C 4. Output shaft 1 5. Micro-step actuator
6. Piezoelectric ceramic 7. Positioning screw 8. Output shaft 2

Fig.4 The Assembly Relationship of Actuator

4.Analysis and calculation of micro-step rotary actuator worktable

4.1 Conditional assumptions

1) Assuming that the length and the spiral radius of the rectangular spring plate are constant when the actuator is subjected.

2) Only consider the axial and circumferential load due to the small deformation.

3) Section A,B,C local forced,won't produce deformation[4].

4.2 Relationship between output angle and input displacement

The deformation coordination relationship as shown in Fig.5.

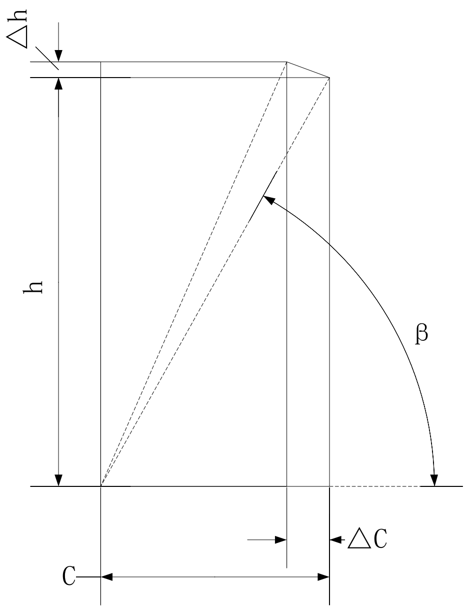


Fig.5 The Deformation Coordination Relationship

The deformation coordination relationship can be obtained from the above assumptions, as follows:

$$C^2 + h^2 = (h + \Delta h)^2 + (C - \Delta C)^2$$

Ignore the higher order items,we can obtain:

$$h = C \tan \beta, \Delta C = R \Delta \varphi$$

Finally,we can obtain:

$$\Delta \varphi = \frac{\tan \beta}{R} \Delta h$$

Where C denotes the circumference of the spiral of the h segment;△h denotes the height variation of helix；△C denotes the length variation caused by △h；φ denotes the central angle corresponding to the helix of the h segment； △φ denotes the spiral angle corresponding to △C.

5.Finite Element Simulation Analysis of Micro-step Rotary Actuator Worktable

5.1 Meshing and load application

Fixed constraints on the middle section of the actuator,axial motion constraints on the spherical structure on both sides.The surface force load is applied to the inner surface of the two columns connected with the transmission shaft,as shown in the Fig.6 and Fig.7.Since the spring is a complex area of stress change, meshing is performed here[5].

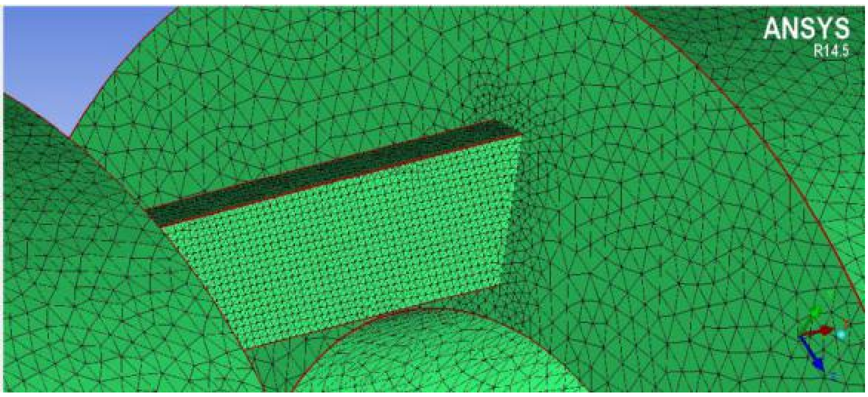


Fig.6 Mesh Refinement at the Spring

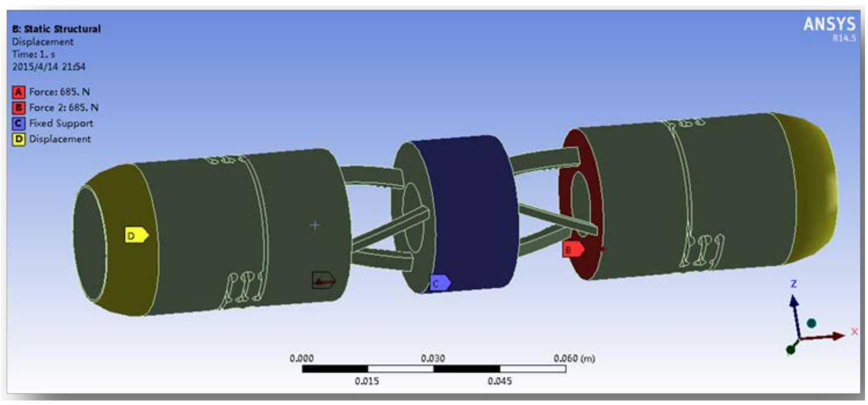


Fig.7 Constraint and Load Application

5.2 Finite element simulation analysis

Orthogonal test method was used to arrange the orthogonal test table for the main factors influencing the structure of the actuator.The orthogonal test factors is shown in Table 1.

Table 1 The Orthogonal Test Factors

Test Number	Spiral Angle (degree)	Dimension (Millimeter)	Cross-section Diameter (Millimeter)	Force (Newton)
1	70	1*3	22	50
2	70	1*4	24	100
3	70	1*5	26	150
4	70	2*4	28	200
5	70	2*5	30	250
6	72	1*3	24	150
7	72	1*4	26	200
8	72	1*5	28	250
9	72	2*4	30	50
10	72	2*5	22	100
11	74	1*3	26	250
12	74	1*4	28	50
13	74	1*5	30	100
14	74	2*4	22	150
15	74	2*5	24	200
16	76	1*3	28	100
17	76	1*4	30	150
18	76	1*5	22	200
19	76	2*4	24	250
20	76	2*5	26	50
21	78	1*3	30	200
22	78	1*4	22	250
23	78	1*5	24	50
24	78	2*4	26	100
25	78	2*5	28	150

The above 25 groups of test data were simulated and analyzed, the simulation and theoretical values of $\triangle\theta$,and the percentage of error between the two can be calculated.The Fig.8 shows the stress distribution nephogram obtained by finite element analysis.It is known that the connecting part of the rectangular spring plate and the actuator is the weak part.Under working conditions, $\sigma_{\max} = 300MPa \le \sigma_s = 343MPa$ .The material is 65Mn.

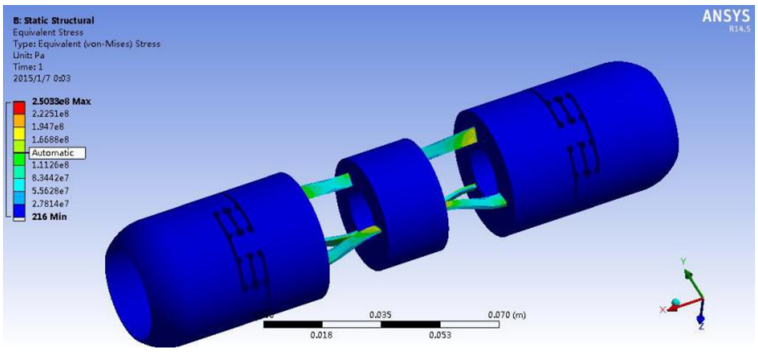


Fig.8 The Equivalent Stress Nephogram

5.3 Analysis of calculation results

The simulation results as shown in the Table 2.The data and its influencing factors are analyzed by using the extreme difference analysis, as shown in Table 3.

Table 2 Test Results

Test Number	Simulation Value ofΔθ (10^-3 rad)	Simulation Value ofΔθ (10^-3 rad)	Error (10^-3rad)	Percentage Error (%)
1	0.713	0.701	0.0116	1.626
2	1.240	1.232	0.0082	0.661
3	1.632	1.625	0.0066	0.404
4	1.259	1.321	-0.0626	4.974
5	1.394	1.462	-0.0678	4.866
6	2.120	2.120	0.0002	0.010
7	2.481	2.488	-0.0069	0.279
8	2.729	2.750	-0.0204	0.747
9	0.290	0.312	-0.0221	7.624
10	1.422	1.569	-0.1473	10.359
11	3.557	3.608	-0.0506	1.421
12	0.622	0.633	-0.0104	1.673
13	1.145	1.165	-0.0206	1.796
14	1.015	1.174	-0.1591	15.664
15	1.074	1.249	-0.1752	16.318
16	1.437	1.486	-0.0496	3.452
17	1.878	1.949	-0.0708	3.772
18	2.869	3.084	-0.2149	7.490
19	1.491	1.805	-0.3136	21.038
20	0.236	0.287	-0.0508	21.545
21	2.902	3.082	-0.1798	6.194
22	4.166	4.574	-0.4087	9.811
23	0.702	0.774	-0.0719	10.246
24	0.514	0.663	-0.1491	28.996
25	0.608	0.787	-0.1796	29.555

Table 3 The Results of Extreme Difference Analysis

<table>
<tr><th>Influencing Factors</th><th>Angle (degree)</th><th>Average Value</th><th>Optimum Solution</th><th>R_J</th></tr>
<tr><td>KB2(Spiral Angle:70°)</td><td>12.5308</td><td>2.506161</td><td rowspan="5">Spiral Angle: 70°</td><td rowspan="5">14.4543</td></tr>
<tr><td>KB7(Spiral Angle:72°)</td><td>19.01823</td><td>3.803647</td></tr>
<tr><td>KB12(Spiral Angle:74°)</td><td>36.87279</td><td>7.374559</td></tr>
<tr><td>KB17(Spiral Angle:76°)</td><td>57.29689</td><td>11.45938</td></tr>
<tr><td>KB22(Spiral Angle:78°)</td><td>84.80238</td><td>16.96048</td></tr>
<tr><td>KC2(Dimension:1*3)</td><td>12.70342</td><td>2.540685</td><td rowspan="3">Dimension: 1*3 Millimeter</td><td rowspan="3">13.9879</td></tr>
<tr><td>KC3(Dimension:1*4)</td><td>16.19644</td><td>3.239287</td></tr>
<tr><td>KC4(Dimension:1*5)</td><td>20.68236</td><td>4.136471</td></tr>
</table>

KC5(Dimension:2*4)	78.29573	15.65915		
KC6(Dimension:2*5)	82.64315	16.52863		
KD2(Cross-section Diameter:22)	44.95087	8.990174		
KD3(Cross-section Diameter:24)	48.27299	9.654598		
KD4(Cross-section Diameter:26)	52.645	10.529	Cross-section Diameter: 23Millimeter	5.67887
KD5(Cross-section Diameter:28)	40.4005	8.0801		
KD6(Cross-section Diameter:30)	24.25174	4.850347		
KE2(Force:50N)	42.71474	8.542948		
KE3(Force:100N)	46.22893	9.245785		
KE4(Force:150N)	49.40352	9.880704	Force:250N	2.8296
KE5(Force:200N)	35.25554	7.051108		
KE6(Force:250N)	37.88321	7.576642		

Figure.9 shows the change trend of the influence of each factor is converted into a graph.

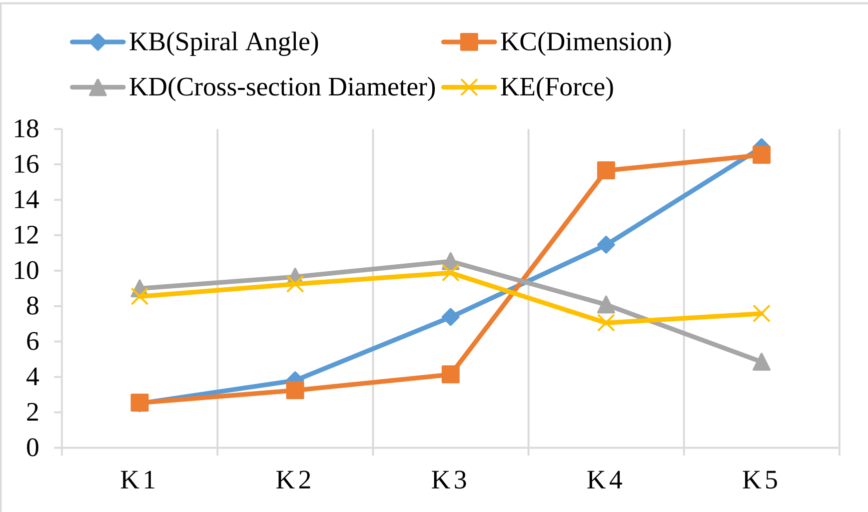


Fig.9 The Change Trend of the Influence of Each Factor

5.4 Analysis results

The following conclusions can be drawn from the above tables and Fig.9 by extreme difference analysis[6]:

1)Among all the factors affecting the experiment,the angle of helix angle is the most important factors that affect the result of experiment,the second is the cross-sectional dimension of the spring plate, the cross-section diameter of the spring piece is the third,and the last is the force applied.

2)The larger the helix angle, the larger the difference between theoretical calculation and simulation results,and the mean value of error increases.

3)The cross-sectional dimension of the spring plate is a factor that is of greater impact after the helix angle.It can be obtained from the analysis that the larger the cross-sectional dimension of the spring plate,the larger the difference between the theoretical calculation value and the simulation value,and the mean value of error increases.

4)For the two factors of the spring cross-sectional diameter and the applied force, the difference between the calculation value and the simulation value is not obvious.

5)It can be concluded from the analysis that the optimal combination among all test groups is:the helix angle of the spring is 70°，the size of the spring cross-section is 1mm * 3mm,the circle diameter of the spring section is 28mm,the applied force is 200N.

6.Conclusions

A novel micro-step rotary actuator worktable is presented in this paper.The working principle of the worktable is analyzed and studied,and its structure is optimized.Due to the use of flexible hinge and symmetrical clamping mechanism,the actuator eliminates the axial clearance while making the clamp more stable，and not easy to deviate from the axis deformation。The influence factors of each structural parameter on the output angle are determined by the the ANSYS simulation experiment and extreme difference analysis.Finally,the optimal structural parameters are determined.

7.References

[1] Jianfang Liu,Shuchen Yang,Zhigang Yang,Guangming Cheng.Study on precision PZT rotary step actuator with inner anchor/loosen[J].Optics and Precision Engineering,2006(4):594-601.

[2] Jingjun Yu,Xu Pei.Graphical Approach to Creative Design of Mechanical Devices[M].Beijing:Science Publishing Company,2014.

[3] Zunqiang Fan,Boda Wu,Zhigang Yang,Guangming Cheng.Precise piezoelectric step rotary micro-actuator with electromagnetic anchoring/lossening[J].Journal of Jilin University(Engineering and Technology Edition),2005(6):601-605.

[4] Jian Shen,Daliang Yin,Shengren Zhu.Design and analysis of a novel precision step rotary actuator[J].Journal of Hefei University of Technology,2010(5):641-643.

[5] Chunhui Yang,Pingan Liu.Finite Element Analysis of arc Flexible Hinge Stress[J].IEEE/IMSNA,2013:978-981.

[6] Shifu Xue,Qingxiang Li.Design of Modern Precision Instruments[M].Beijing:Tsinghua University Press,2010:184-217.