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Modeling and Force Analysis of an Electrothermal Micro Gripper with Amplification Compliant Mechanism

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Abstract

This work reports a novel design of a micro gripper, in which V-shaped electrothermal actuators are used to create gripping force and a compliant mechanism is integrated to amplify displacements of the actuators. The gripper is designed to handle micro samples of various sizes from 5 μm to 50 μm by applying appropriate driving voltages. Those voltages are ranged from 5 V to 25 V, which are relatively low in comparison with driving voltages of the electrostatic micro grippers. The compliant mechanism with amplifying ratio 5.2, arranged between the actuators and the jaws, is aimed to compensate small strokes of the actuators. Simulation by Finite-Element Analysis has also been carried out to confirm results of the theoretical calculation and designing process. The micro gripper can be implemented in micro devices such as micro robots or micro assembling systems, in which it can perform gripping and transporting tasks.

Keywords: Micro gripper, V-shaped actuator, Compliant mechanism.

1. Introduction

Today acronym MEMS, which stands for Micro Electro Mechanical System, has become more and more familiar with all of us. MEMS technology has been widely researched and rapidly developed since the last decades of twentieth century. Nowadays, MEMS products have been applied into numerous areas such as biomedical engineering, automobile industry, military industry, aviation and space technology etc. as well as into human daily life. In those micro systems and devices, there is a demand for micro grippers, which can manipulate tiny objects with sizes ranged from few micrometers to hundreds of micrometers. Various types of micro actuators have been used for driving those grippers, including electrostatic [1-3], piezoelectric [4-6], shape-memory alloys SMA [7-9] and electrothermal [10, 11]. In comparison with other actuation methods, the micro electrothermal grippers have the advantage of lower driving voltage (comparing with the electrostatic grippers), simple fabrication process (comparing with the piezoelectric and SMA grippers) and large generated forces. On the other hand, those thermal devices also have some disadvantages, such as thermal dependence, lower working frequencies and relatively small displacement. To overcome the last disadvantage, using of the amplifying compliant micro mechanism is an effective solution.

Compliant mechanisms, which are jointless and monolithic mechanical device, are very appropriate to use in the MEMS systems instead of the conventional mechanisms with classic revolute and prismatic joints [12-14]. Another reason for implementation of the compliant mechanism into micro gripper is the output motion. All the electrostatic, electrothermal and piezoelectric micro actuators produce relatively small strokes. The compliant mechanisms can help to amplify those displacements and make them proper for gripping task. In this work, the authors present the micro gripper driven by the V-shaped electrothermal actuators and amplifying mechanism, which can grip the micro samples sized up to 50 μm and can be applied in micro robot or micro analysis systems.

2. Theoretical calculation

2.1. Configuration and geometrical displacements

2.1.1. Working principle

Figure 1 shows the configuration of the micro gripper, which consists of three main parts: actuating unit with the V-shaped electrothermal actuators (1), amplifying unit with the compliant mechanism (2) and gripping jaws (3). The beams of the V-shaped actuators are fixed at one end with the anchors (4), the other end of the beams are connected to the main beam (5). When applying a driving voltage, the wings

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of the V-shape beam will expand and push the main beam (5) forward. The compliant mechanism (2) with the flexural joints (6) is designed to convert displacement in y-direction into rotation movement of the jaws (3), and also to amplify displacement of the actuators.

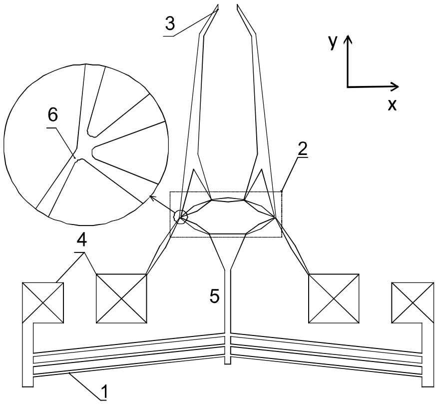

Fig. 1. Configuration of the micro gripper

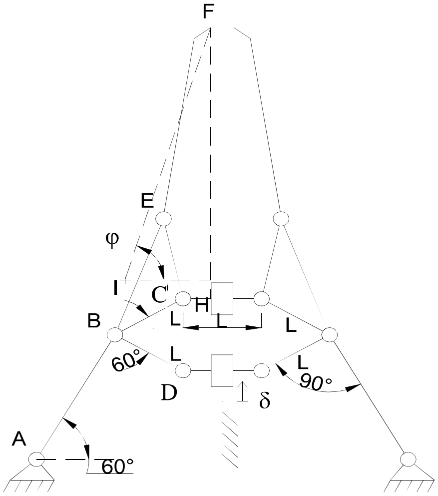

Fig. 2. Equivalent model of the micro gripper

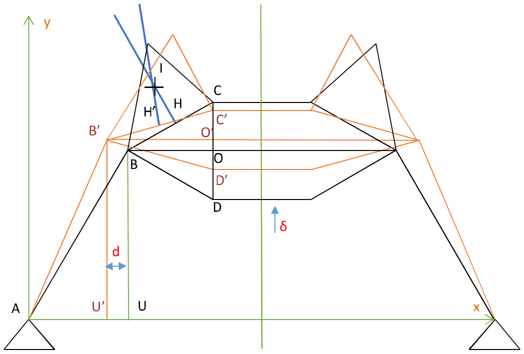

Fig. 3. Displacement of the links

2.1.2. Geometrical displacements

Because only geometrical displacements of the compliant mechanism and the jaws are taken into consideration, we substituted the flexural joints with revolute joints and omit the elastic forces. The equivalent model of the gripper is shown in figure 2. Calculation is being carried out with only one wing due to the symmetries of the gripper structure.

Because three points F, B and C belong to one rigid body, in order to find out displacement of the tip F of the jaw, position of the points B and C must be determined. In figure 3 we can see under the input displacement d, the jaw i.e. BC will rotate an angle α. Using geometrical equations, the displacements of the point B and C in *x*-direction and *y*-direction can be calculated as:

$$d_D^y = DD' = x + OO' = x + \sqrt{AB^2 - (AU - d)^2} - AB\sin(B\hat{A}U) \quad (1)$$

$$d_C^y = CC' = x - OO' = x - \sqrt{AB^2 - (AU - d)^2} + AB\sin(B\hat{A}U) \quad (2)$$

$$d_B^x = BB'_x = \sqrt{BC^2 - (CO - x)^2} - \sqrt{BC^2 - CO^2} \quad (3)$$

$$d_B^y = BB'_y = OO' = \sqrt{AB^2 - (AU - d)^2} - AB.sin(B\hat{A}U) \quad (4)$$

Where B',C',D' are the new position of B, C, D under influence of the input displacement d. From position of BC and B'C' we can find the virtual center of rotation I as below:

$$I = \begin{bmatrix} \dfrac{\overrightarrow{B'C'_y} \times \overrightarrow{BH_x} - \overrightarrow{BC_y} \times \overrightarrow{B'H'_x}}{\overrightarrow{B'C'_y} - \overrightarrow{BC_y}} \\ \dfrac{\overrightarrow{B'C'_y} \times \overrightarrow{BH_y} - \overrightarrow{BC_x} \times \overrightarrow{B'H'_x} - \overrightarrow{B'C'_x} \times \overrightarrow{BH_x} - \overrightarrow{BC_y} \times \overrightarrow{B'H'_y}}{\overrightarrow{B'C'_y} - \overrightarrow{BC_y}} \end{bmatrix} \quad (5)$$

And the rotation angle can be expressed as follows:

$$\cos\alpha = \frac{\dfrac{L}{2} - d + \sqrt{3L^2 - 3\left(\dfrac{L}{2} - d\right)^2}}{2L} \quad (6)$$

Where the length of BC, CD and BD at the initial position is *L*. And finally, we have the lateral displacement of the jaw tip *F* as well as the amplifying ratio K_A of the compliant mechanism:

$$\Delta = \left(\cos(\varphi - \alpha) - \cos\varphi\right).IF \quad (7)$$

$$K_A = \Delta / d = 5.2 \quad (8)$$

For example, there is input set of parameters with AB = 200 μm, BD = BC = 100 μm, FH = 600 μm, and the angles are designed with the values as shown in figure 2. We can calculate that for creating

25 μm displacement for one gripper jaw, only 4.8 μm input displacement is needed.

2.2. Displacements of the V-shaped actuators

Calculation for the V-shaped electrothermal actuators has been presented in [15]. According to that paper, if we have the thermal actuator with dimension as shown in figure 4, we can calculate force *F* and displacement *S* as follows:

$$S = \sqrt{l^2 \sin^2 \sin^2 \ell + 2l.\Delta l} - l.\sin \ell \qquad (9)$$

$$F = 2nEbh\frac{\Delta l}{l}\sin \ell \qquad (10)$$

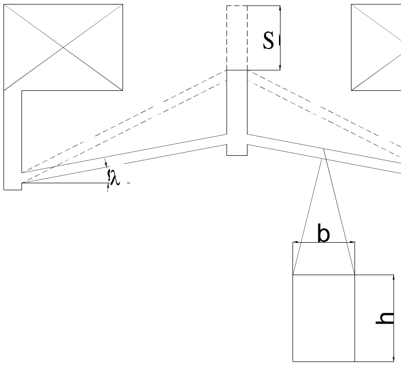

Fig. 4. V-shaped actuator

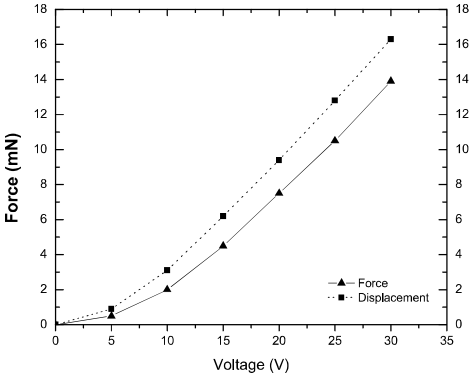

Fig. 5. Relation between voltage and displacement, force of the actuator

Where *b*, *h* and *l* are the width, height and length of the actuator beam. ℓ is the slope angle of the beam. And *n* is the number of the beams in the actuator. In figure 5 is the graph showing the relation between driving voltages and forces, as well as displacements of the V-shaped actuator.

3. Simulation

3.1. Stiffness calculation

Simulation was carried out with simulating thermal-expansion force located at the tip of the main beam (5) F_{S1} equals 100 μN (see figure 6). Assuming that deformation in the gripper structure is purely elastic, meaning that relation between the input force and displacement of the gripper jaws is linear. With the value 3.15 μm of output displacement, we can calculate the stiffness of the gripper structure: $k_S = F_{S1}/3.15 = 31.75$ μN/μm.

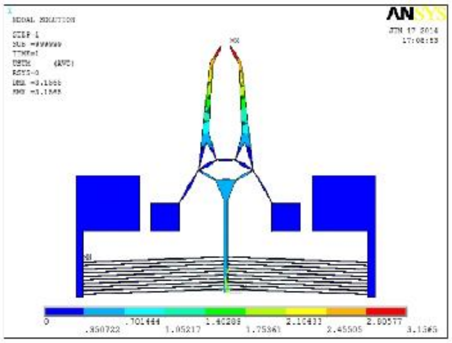

Fig. 6. Displacement of the gripper jaw

Similarly, with simulating gripping force $F_{G1} = 100$ μN located on the tip of the gripper jaws, the displacement obtained by simulation is 2.48 μm (see figure 7). Therefore, the stiffness of the gripper jaw can be calculated as: $k_G = F_{G1}/2.48 = 40.32$ μN/μm.

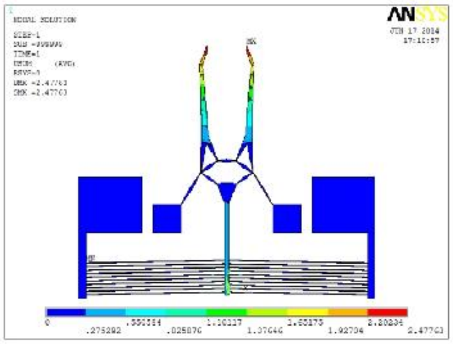

Fig. 7. Simulation of gripping force

3.2. Displacements

To drive the gripper, the V-shaped electrothermal actuator with following specification was chosen: number of beams n = 10, the length of each beam l = 750 μm, beam width b = 4 μm, beam height h = 30 μm, and the range of the driving voltages 0÷30 *V*. Table 1 shows the relation between voltages and displacement *S* of the actuator. We have to take into consideration that simulation was carried out just only for the thermal actuator itself.

Table 1. Relation between displacements and driving voltages of the actuator

U(*V*)	5	10	15	20	25	30
S(*μm*)	1.76	3.12	5.39	8.56	12.64	17.63

To simulate whole system with AB = 200 μm, BD = BC = 100 μm, FH = 600 μm, we can find the displacements of the jaw tip of the gripper (see in table 2). In section 2.1, we have already found the amplifying ratio of the gripper K_A is 5.2. Therefore, we can also find out the displacements δ of the thermal V-shaped actuator while it is integrated into the gripper. Deviation between displacements δ and S can be explained by the fact that when the actuator is connected to the compliant mechanisms and the jaws, it will operate as a member in the complex system and can only be able to produce smaller displacement.

In figure 8, we can see simulation result of the displacement Δ = 18.46 μm of the jaw under the driving voltage of 20 *V*. The calculated and simulated displacements of the gripper are shown in figure 9. The curve of the theoretically calculated displacements and the curve expressing simulating results are almost identical.

Table 2. Relation between driving voltages and displacements Δ and δ

U(V)	5	10	15	20	25
Δ(μm)	3.80	6.74	11.62	18.46	27.26
δ(μm)	0.73	1.29	2.23	3.55	5.24

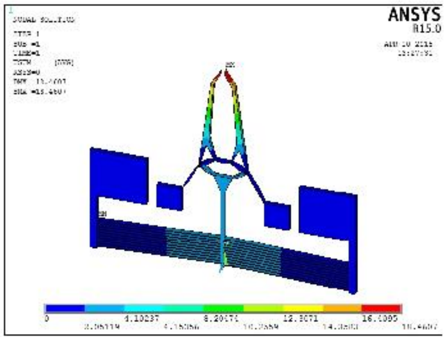

Fig. 8. Simulation of complex gripping system

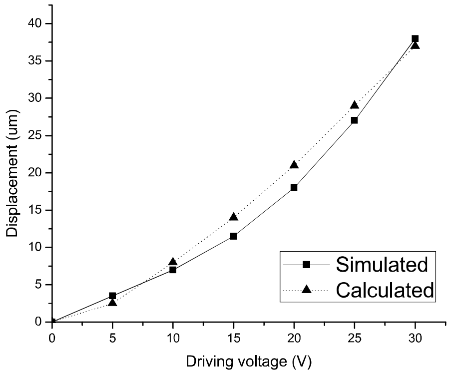

Fig. 9. Displacements of the gripper

Comparing S and δ, we can find the compressing ratio K_C between displacements of the main beam of the V-shaped actuator when it works alone and when it is integrated into the gripper:

$$K_C = S/\delta = 2.4 \tag{11}$$

3.3. Calculation of the minimum voltage for gripping micro objects

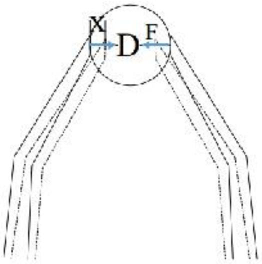

Fig. 10. Jaws and micro object

In figure 10, we can see the jaws and the micro sample with diameter *D μm*. Supposed the initial gap between the jaws is *G μm*.

The displacement of one jaw to approach the object is calculated as follows:

$$x = \Delta = (G-D)/2 \tag{12}$$

Using equation (8) and (11), the displacement S of the V-shaped actuator can be expressed as:

$$S = K_C.\delta = K_C.\Delta/K_A \tag{13}$$

From (13) we can establish relation between the minimum voltage for driving the micro gripper and the sample diameter in form of the graph as shown in figure 11.

3.4. Calculation of the gripping force with the micro sample with diameter 30 μm

From (12), with the initial gap G=60 μm, we can calculate the displacement of one jaw to approach the object as: $x = \Delta = \dfrac{G-D}{2} = 15\,\mu m$

From the relation between the driving voltage and displacement (Figure11 - table 2), if we consider that this relation with U ranged from 15 *V* to 20 *V* is approximately linear, corresponding with x = 15 μm, we can obtain U_{min} = 17.47 *V*.

The process of handling the micro object can be split into 2 following phases. Firstly, the voltage increases to the value of U_{min}, and the jaws are approaching and touching the object. And secondly, the voltage continues to increase to U*, and generates the gripping force F_k. In this second phase, the gripping force has the value equaling the elastic force generated when one jaw is compressed by Δ_x, and F_k can be expressed as follows:

$$F_k = k_G.\Delta_x \Rightarrow \Delta_x = F_k / k_G$$

The stiffness k_G = 40.32 *mN/mm* has been obtained by simulation (*Fig. 7).* We can calculate the voltage U for gripping the micro sample with diameter D with the gripping force F_k as follows:

$$U = U_{min} + U_x \quad (14)$$

From (14), the gripping force generated while working with the sample with diameter 30 *mm* can be calculated as shown in the table 3.

Table 3. Relation between driving voltages and gripping force F_k

F_k(µN)	**D_x(µm)**	**U_x(V)**	**U(V)**
100	2.48	3.26	20.73
200	4.96	6.97	24.44
300	7.44	10.71	28.19
400	9.92	13.25	30.73
500	12.40	15.57	33.04

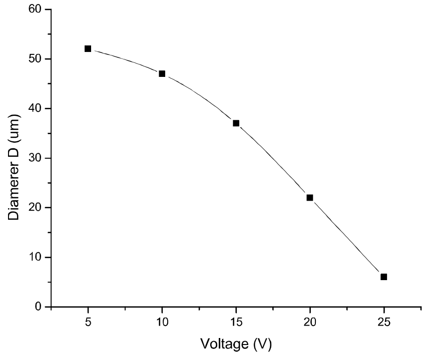

Fig. 11. Relation between sample diameter and driving voltage

4. Conclusion

In this paper, the design, calculation and simulation of the electrothermal micro gripper have been presented. The compliant mechanism with the amplifying ratio K_A= 5.2 was used to magnify the input displacement of the V-shaped actuator. The gripper is designed to work with the driving voltages ranged from 5 *V* to 25 *V*, and to grip the micro object with diameter ranged from 5 *mm* to 50 *mm*. This device can be fabricated by the bulk micromachining technologies using only one photomask on a SOI (silicon-on-insulator) wafer. Simulation has been carried out to confirm the results of calculating work. The micro gripper can be implemented in micro devices such as micro robots or micro assembling systems, in which it can perform gripping and transporting tasks.

Acknowledgments

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