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Experimental research and analysis of three-finger micro-tweezers

HUANG Wen-hao, XING Hao

(*Department of Precision Machinery and Precision Instrument, University of Science and Technology of China, HeFei* 230027, *China*)

Abstract: A new type of three-finger micro-tweezer driven by electro-static force was developed for stable manipulation and assembly of micro devices. The whole system consists of micro-tweezers and a specially designed high frequency AC power supply. The free end of the fingers closes and opens with the increase and decrease of the voltage. The tweezers can grasp and manipulate micro objects at size from 30～100 μm. A quantitative simulation method based on boundarx element method(BEM) and equation of energy conservation is introduced to analyze the non-linear behaviors of the tweezer closure. The simulation results agree well with the experimental data.

Key words: three-finger micro-tweezer; particulation; manipulation; simulation

1 Introduction

With the development of micro-electro-mechanical structure (MEMS), grasping, manipulating and assembling of micro objects are quite fascinating. New tools for these purposes have been developed rapidly. However, most of these researches are focused on two-finger micro-tweezers[1～3]. The stability and application of two-finger micro-tweezers in manipulation and assembly are very limited in grasping sphere, columnar or complicated micro objects[4]. In order to grasp particles more steadily, carbon fibers are used to create the three fingers of micro-tweezers, which is driven by a power supply with a high frequency alternative potential. In this paper, the manufacture process of the three-finger micro-tweezers and the design considerations of the power supply will be introduced. Experiments about closure, opening, grasping and manipulating of micro objects at size from 30～100 μm are presented. In order to explain the non-linear closure process, a simulation method based on a hybrid method of boundary element method (BEM)[5] and equation of energy conservation will be discussed. The results show that the method is very effective.

2 Three-finger microtweezers

2.1 Fabrication of three-finger micro-tweezers

The most important challenges in the manufacture of the three-finger micro-tweezers are how to divide the three fingers symmetrically in space and how to apply the electrostatic forces to obtain the symmetrical movements of the fingers. Here, carbon fibers and optical fibers are used to make the three-finger micro-tweezers. With remarkable properties in mechanics and e-

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lectrical conduction the carbon fiber is suitable for electromechanical devices in micro scale. Three carbon fibers, with a diameter of 5μm, were attached individually in the joint gap between each two of the three tightly tied optical fibers, whose diameter is 125 μm, and this process could ensure the three fingers to be parallel and symmetrical in space. Free ends of the carbon fibers act as the fingers and the other ends are fixed on the electrodes, respectively. The electrodes are formed by three Au films deposited on a slide. With all these procedures, we got the three-finger micro-tweezers. Fig. 1 is the schematic illustration of the three-finger micro-tweezers. The length of the fingers is 2.0 mm; the distance between each two of the fingers is 108 μm. Fig. 2 shows the optical micrograph of the actual three-finger micro-tweezers.

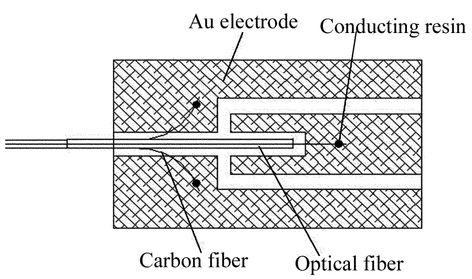

Fig. 1 Schematic illustration of the three-finger micro-tweezers

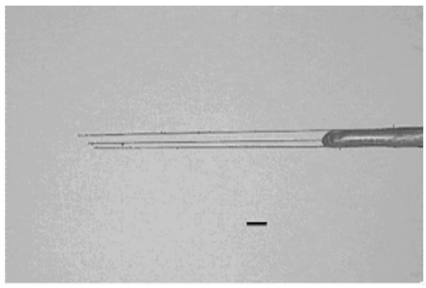

Fig. 2 Optical micrograph of the three-finger micro-tweezers

In order to close and open the three fingers together, a power supply with an alternative high frequency was designed and the waveform is shown in Fig. 3(a). From Fig. 3(b), at each time position (t_0), only one of the finger is equally biased between the two sides (Arm 1 in this illustration), i. e. $V_{12}=V_{13}\neq V_{23}$. At such electrical potential, non-symmetrical movements of the three fingers are expected if DC voltage is adopted. However, by using AC voltage, the bias voltage between every two fingers is rotating. If the frequency is fast enough, we can achieve the symmetrical movements of fingers toward the geometrical center. The frequency of AC voltage is selected by using a value which is far away from the resonance frequency($\omega_1=1.5$ kHz, $\omega_1=9.8$ kHz) of the fingers. We choose 20 kHz as the frequency of the power supply.

2.2 Experiment

We carried out the experiment of the three fingers closing, grasping and manipulating the micro objects under the optical microscope.

In the experiment, the electromechanical response of the micro-tweezers was investigated by applying voltages to the electrodes. With the increasing of peak voltage value, every two fingers of the three got closer to each other simultaneously and could return to their original positions with the voltage removed. We found that every finger of the micro-tweezers had an elastic response before closed. As the voltage (V_0) increased to 162 V, the fingers of the tweezers closed suddenly. Fig. 4 shows the closure process of the micro-tweezers. During the voltage increasing the vibration was not observed within the optical microscope resolution limit.

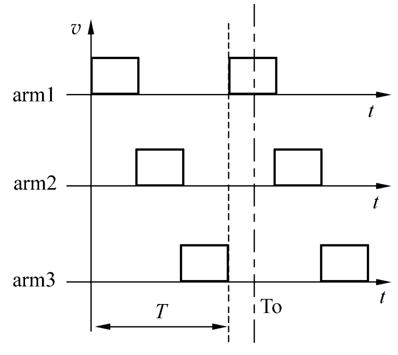

Fig. 3(a) Waveform of voltage used to drive the three-finger micro-tweezers.

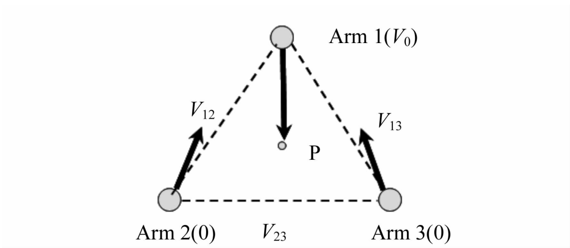

Fig. 3(b) Illustration of voltage on each finger at time t_0.

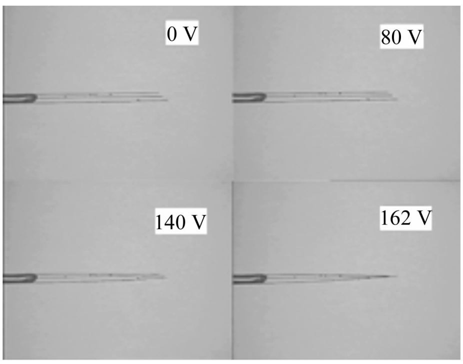

Fig. 4 Optical micrographs of the three-finger micro-tweezers at 0, 80, 140, 162 V

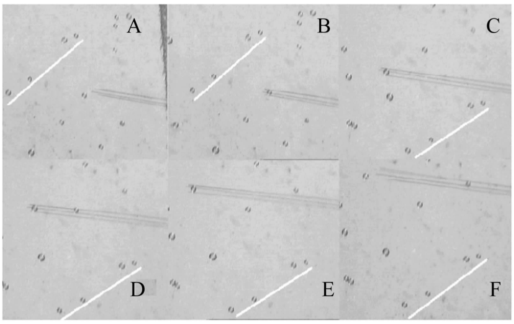

Fig. 5 Micrograph of the process of manipulating the polymer ball

The three-finger micro-tweezers could grasp particles at size from 30 μm to 100 μm. Fig. 5 shows the process of manipulating a polymer ball whose diameter is about 50 μm. In this experiment, we use the non-conductive objects. However, we believe that we can also grasp conductive things if an insulate film is covered on the fingers. In Fig. 5, A shows the tweezers approaching the ball; B is the micrograph of grasping the ball; C～D show the movement of the ball; from the F we can see that the ball has been put down. We found the manipulation was stable and repeatable in the experiment.

3 Simulation method

The fingers of the micro-tweezers could be considered as a system of three isolated conductors embedded in a uniform vacuum dielectric medium. The process of the three fingers closing is also regarded as the elastic energy to balance with the electrostatic energy. And the elastic energy is

$$G_{\text{elas}} = \frac{3\pi E r^4}{2}\int_0^L \left(\frac{\partial^2 y}{\partial x^2}\right) \mathrm{d}x \ , \qquad (1)$$

where y is the displacement at x position, r is the radius of the finger, L is the length of the finger, E is the Young's modulus. Because the deformation of the fingers with the voltage increasing is very minute, the distributed forces acting on the finger may be assumed as uniform forces. From the charge density discussed above, the electrostatic energy is

$$G_{\text{elec}} = -\frac{1}{2}CV^2 = -\frac{1}{2}QV \ , \qquad (2)$$

Because the charges only distribute on the finger surface, an exterior region is more efficient. Since the direct BEM needs to define a far field boundary, indirect BEM formulation is applied here, in which only the surface of the conductors needs to be discretized. For the Laplace equation, the indirect BEM formulation is

$$u_i = \int_\Gamma u^* \sigma \, \mathrm{d}\Gamma \ , \qquad (3)$$

where u_i is the potential at i point, σ is the source density, whose physics meaning is the difference between the differential of interior and exterior potential

$$\alpha_i = -\varepsilon \frac{\partial u_i}{\partial n} \quad , \tag{4}$$

u^* is Green function, u^* is the potential at i point generated by the charge at j point in 2D.

$$u^* = \frac{1}{2\pi}\ln\left(\frac{1}{R}\right) \quad , \tag{5}$$

With the enlargement of R, $u^* \to \infty$, we can introduce a constant D, which is large enough, to ensure $u \to a$ constant, when the boundary is discrete to N constant elements.

$$u_i = \sum_{j=1}^{N} \sigma_j \int_{\Gamma_i} u^* \, d\Gamma + D \quad , \tag{6}$$

For the entire N distributed boundaries, there are N equations, but $N+1$ unknown quality. So an additional equation based on the feature of inductive charges is introduced

$$\int_{\Gamma} \sigma \, d\Gamma = 0 \quad , \tag{7}$$

Equation (6) and (7) may be solved for α on the surface at a certain u. Then the forces acting on the fingers can be calculated.

Here, the small deformation assumption is used for computing the deformed shape of the fingers. First, a small voltage is applied on the fingers on the initial position. The charge density on the surface is calculated by BEM under this condition. The deformation can be achieved by the equation of electrostatic energy and elastic energy. And the achieved deformation replaced the initial position above. Then the iterate method can be used continuously.

The ultimate calculated result is 171 V, which is very close to the experiment result 162 V. And the simulated process is familiar with the experiment very much. When the displacement of the tip is about 2/3 to the origin displacement, the three fingers are closed. Fig. 6 is the displacement of one finger tip compared with the experiment data.

4 Conclusions

We have proposed an appropriate structure of three-finger micro-tweezers. The tweezers are suitable for grasping and manipulating micro objects at size of 30～100 μm. A feasible simulation method is discussed. Although there are some deficiencies in manufacturing processes, the prospect of three-finger micro-tweezers is very promising.

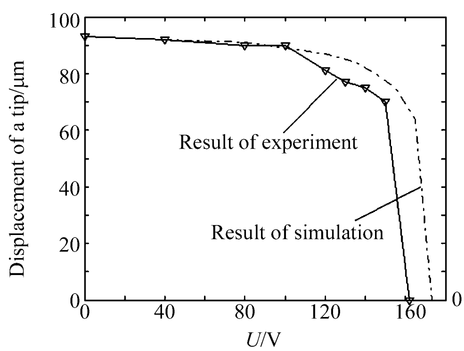

Fig. 6 Displacement of one finger tip with the potential applied

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Brief professional biographies of the authors:

HUANG Wen-hao is currently a professor in Department of Precision Machinery and Precision Instrumentation at University of Science and Technology of China. His research interest include nano metrology, two-photon micro-fabrication, micro manipulation, etc. Tel: 86-551-3603372; E-mail: whuang@ustc.edu.cn

XING Hao is currently a graduate student in Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China. Tel: 86-551-3621415; E-mail: xingh@mail.ustc.edu.cn