A LOBSTER-SNIFFING INSPIRED ACTUATOR FOR MANIPULATION OF MICRO-OBJECTS VIA CONTROLLING LOCAL FLUID

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ABSTRACT

Inspired by lobsters' sniffing behavior, a bimorph actuator is proposed for particle manipulation. The engineering implementation of this lobster-tiny-hair-like capturing device is achieved by surface micromachining. This device actuates electrostatically and drives the micro-objects via disturbing the fluid field and manipulates the Reynolds number of the surrounding fluid to achieve the function of micro-object manipulation. Numerical simulations are carried out to obtain the design criteria. Preliminary experimental results demonstrate the feasibility and functionality of our lobster-sniffing inspired actuator via the micro-object manipulation in liquid environment.

Keywords: Reynolds number, Biomimic MEMS, Electrostatic actuator, Bimorph

INTRODUCTION

The manipulation of micro-objects has a variety of applications in medical science and clinical diagnosis. For the further demand of investigating the interactions, MEMS technology offers a size-matched tool [1]. Numerous MEMS devices are designed for bio-objects capturing such as microgripper [2, 3], pneumatic microcage [4] and the conjugated polymer actuator [5]. Most of them make use of the clamping mechanism and catch particles via direct contact. In addition, numerous researches focusing on the manipulation of micro-objects via field variations control have been proposed lately. The force in optical tweezers, for example, is resulted from the momentum transfer of refraction light to trap the targeted object. Dielectrophoresis (DEP) is based on the concept of polarizing objects with applied electric field. The capability of controlling living cells using both methods has been demonstrated. However, the equipment setup of optical tweezers is large and cost relatively high while the application for the manipulation of different cells by DEP is still a challenge.

The rich variety of mechanisms employed by swimming organisms has long been an inspiration for engineers and scientists. In Nature, lobsters sniff for finding food, a suitable mate or to avoid predators by flicking their antennules (i.e. the second pair of antennae on the head of a crustacean) and capturing fine patterns of odor molecules from the surrounding fluid. Lobsters' sniffing process could be classified into two stages: they first change local fluid field by flicking their antennules with different velocities to bring odor molecules closer and then get in contact with their chemosensory aesthetasc hairs to smell. The way how lobsters bring targeted particles closer could be explained by using the concept of boundary layer and Reynolds number which has been studied by M. A. R. Koehl *et al.* [6]. The Reynolds number is mathematically represented as $\mathrm{Re} = ul/v$, where u is the velocity, l is the characteristic length and v is the kinematic viscosity. When a fluid moves relative to a solid body, the layer of fluid in contact with the surface of the body does not slip with respect to that surface. Hence, a velocity gradient, i.e. boundary layer, develops in the fluid between the surface and the freestream flow. The faster the relative velocity is (higher Re), the thinner the boundary layer is. On the contrary, the slower the relative velocity is (lower Re), the thicker the boundary layer is. In order to imitate the way lobsters control local fluid, we fabricate sets of biomimic actuator to realize micro-object manipulation in liquid environment.

DEVICE DESCRIPTION

Figure 1 shows SEM pictures of finger sets which are designed to be actuated by electrostatic force. The fingers composed of bimorph beams curl up after the release process due to the mismatch of thermal expansion coefficients between aluminum layer and chromium layer. When there is a relative motion between fingers and their surrounding fluid, a boundary layer is formed around the fingers. First, the fingers are electrically driven in order to move downward by applying voltage on the bottom electrodes. Then the fingers move upward slowly with decreased applied voltage. As illustrated in figure 2, during the fast downstoke, the finger set acts as a filter since the boundary layer is thin enough to allow the fluid to penetrate through the fingers' spacing. While fingers return to their original position slowly, the finger set could be considered as a paddle because thick boundary layers fill up the gaps between each finger. For the paddle mode of our actuator finger set, the return motion generates a drag force to bring the targeted particles

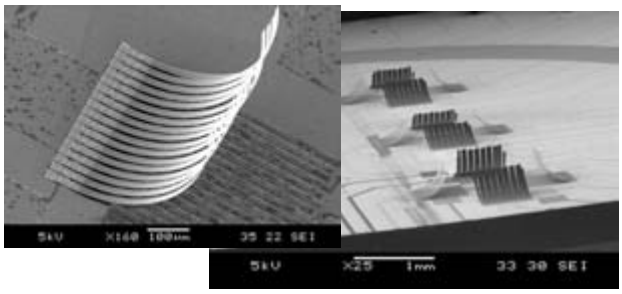

Figure 1. Scanning electron microscope (SEM) pictures of lobster-sniffing inspired electrostatic-actuated fingers in an array arrangement. The finger is 300 μm in length, 250 μm in height, 20 μm in width, 0.8 μm in thickness and 10 μm in the gap spacing.

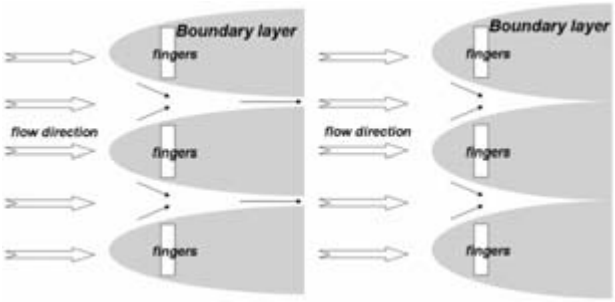

Figure 2. Schematic illustration of two operation modes with different fluid velocity. The left is filter mode (fast velocity). The right is paddle mode (slow velocity).

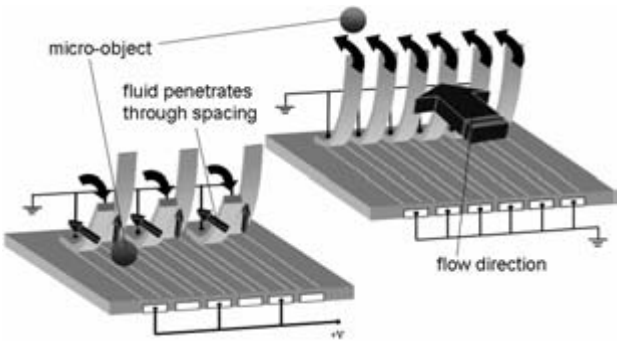

Figure 3. Voltage control strategy: pull down odd and even fingers separately (filter mode) and then release all fingers together (paddle mode).

closer to the fingers. The bottom electrode is connected to a high potential terminal while the fingers are electrically grounded. An insulation layer is fabricated above the bottom electrode to prevent it from short circuit effect. When the finger sets are actuated continuously, the particle could move toward a specific direction based on our temporal and spatial voltage control. Figure 3 illustrates our voltage control strategy to achieve micro-object manipulation in liquid. Odd and even fingers are driven downward separately to enhance

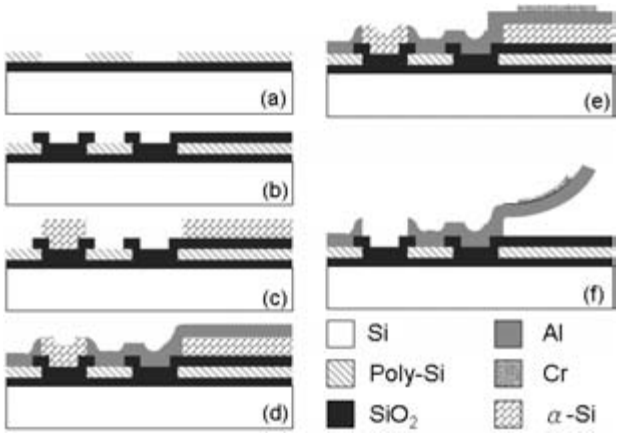

Figure 4. Fabrication process of the lobster-sniffing inspired actuator.

the filter effect and return to their initial position together for giving rise to a higher drag force. In our design, the finger sets are arranged in an array configuration with each row of finger set serving one way drag.

FABRICATION

The micro-fabrication of the lobster-sniffing inspired actuator is realized by surface micromachining technique. On a standard p-type <100> silicon wafer, thermal silicon dioxide is grown first to form an electric insulation layer. This is followed by depositing poly-silicon with phosphorous doping which is patterned, then, to serve as bottom electrodes and wires as shown in figure 4(*a*). Next, PECVD silicon dioxide is conformally deposited to function as the second insulation layer to prevent short circuit effect and bubble formation during operation in liquid. Then, amorphous silicon deposited by PECVD is chosen to be the sacrificial layer and patterned by RIE to define anchor as illustrated in figure 4(*b*) and 4(*c*), respectively. The bimetal structure of the biomimic actuator is fabricated using lift-off technique to define aluminum layer and chromium layer in sequence. Finally, as shown in figure 4(*f*), all exposed poly-silicon is removed by XeF_2 to release actuator and the fingers curl up due to residual stress.

DESIGN AND SIMULATION

The results of model analysis using CoventorWare help modify our design and make sure that the first vibration mode is an up-and-down stroking mode which is exactly the mode we want the fingers to be operated under. The thicker the finger is, the less coupling effect among different modes is [7]. This is because thicker finger leads to a stronger stiffness such that higher energy is required to excite other higher vibration modes. A quasi-static analysis based on Rayleigh-Ritz method is employed to investigate the pull-in voltage [7, 8].

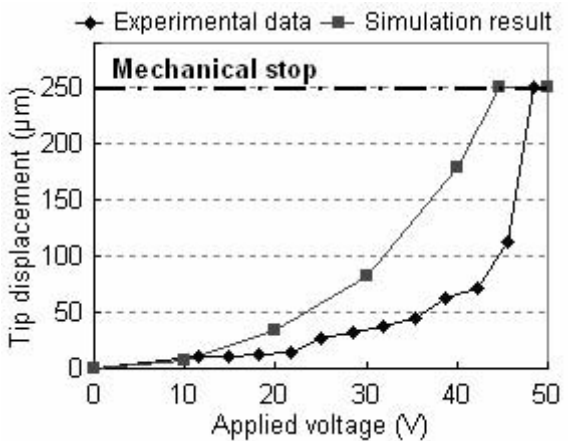

Figure 5. Tip displacement vs. applied voltage.

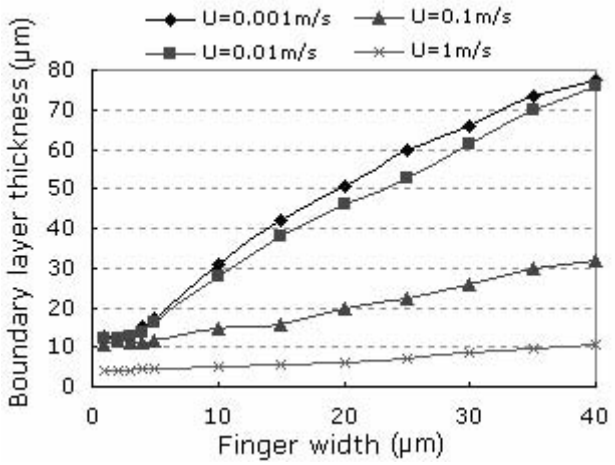

Figure 6. Boundary layer thickness vs. finger width for various actuating velocity ranging from 0.001 to 1 m s^{-1}.

According to the analysis, the width of the finger has little effect on the pull-in voltage. Actuating fingers with longer length or thinner thickness have smaller mechanical stiffness to compete against electrostatic force and could be driven by lower voltage. Previous studies by Legtenberg and co-works have also indicated that pull-in voltage depends highly on the initial gap spacing at the clamped edge of the structure [8]. Figure 5 shows the tip displacement of the finger versus the applied voltage for both simulation and experimental results. The differences come from the parameter variation due to fabrication constraint.

As for the fluid field analysis, a commercial software package, CFDRC, is utilized to simulate this complicated problem. Figure 6 shows the simulation results of boundary layer thickness versus finger width for different actuating velocities ranging from 0.001 m s^{-1} to 1 m s^{-1}. It shows that higher relative velocity between the finger and its surrounding fluid gives rise to thinner boundary layer. On the contrary, slower relative velocity leads to thicker boundary layer. Finger width has little

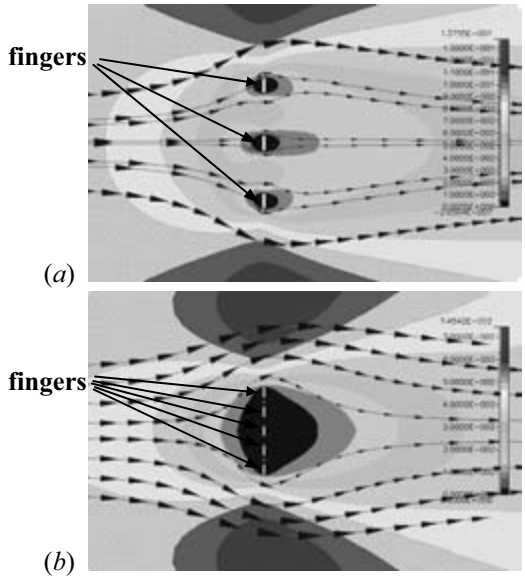

Figure 7. Simulation results of fluid flowing through finger set. (*a*) finger width: 5 μm, gap spacing: 15 μm, at a velocity of 1 m s^{-1}. (*b*) finger width: 5 μm, gap spacing: 5 μm, at a velocity of 0.05 m s^{-1}.

effect on boundary layer thickness at high relative velocity but the influence of the finger width to the boundary layer thickness becomes more obvious with the decrease of the relative velocity. These results guide us to optimize the parameters design of our biomimic actuator fingers to minimize the effects of micro-fabrication variations and operation uncertainties. The simulation results of fluid flowing through actuator finger sets are simulated by using CFDRC and shown in figure 7. Figure 7(*a*) shows the filter mode in which fluid penetrates through the fingers' spacing. Figure 7(*b*) shows the paddle mode in which boundary layer is thick enough to stem the fluid flowing through the fingers' spacing. These simulation results indicate the feasibility of the voltage control strategy to operate odd and even fingers separately or simultaneously to mimic the functions that lobsters use to find food and a suitable mate via capturing odor molecules from the surrounding fluid.

EXPERIMENTAL RESULTS AND DISCUSSION

In order to study the dynamics of the curled finger actuator, Polytech laser Doppler vibrometer (LDV) is utilized to characterize the resonant frequencies of the actuator fingers. Figure 8 shows the resonant frequencies measured in air where the first vibration mode appears at 5.2 kHz, the second vibration mode appears at 12.5 kHz and the third vibration mode appears at 20.3 kHz. It is expected that the resonant frequencies shift slightly to higher values while operating in liquid since liquid environment is highly damped and more viscous than air.

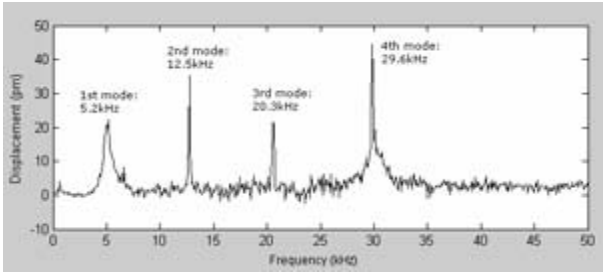

Figure 8. Resonant frequencies measurement via Polytech Laser Doppler Vibrometer. The testing finger has 300 μm in length, 250 μm in height, 20 μm in width and 0.8 μm in thickness.

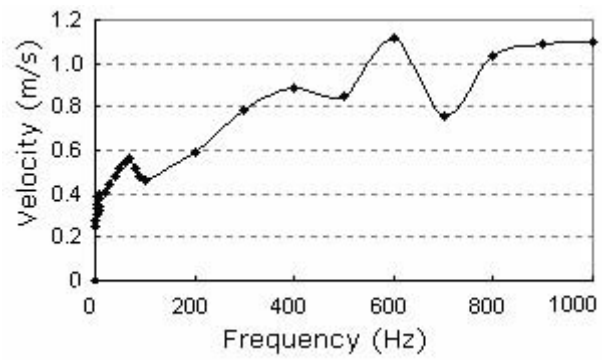

Figure 9. Tip velocity versus the frequency of 25 Vpp AC applied voltage measured by Polytech LDV.

Figure 9 shows the relationship between tip velocities versus the frequency of a 25 Vpp AC applied voltage. Within 25 Vpp AC voltage signal, the measured tip velocities varies ranging from 0.2 m s^{-1} to 1.2 m s^{-1} for the frequencies from low up to 1 kHz. Referring to the measurement results, a ramp voltage shape is applied for actuating the finger sets properly.

We have successfully tested our device in both air and 3M Fluorinert FC-40 liquid, whose relative permittivity is 1.89. After testing the finger actuator in air successfully, the actuator is submerged in Fluorinert. The required voltages to snap down the actuator fingers in air and Fluorinert are slightly different. The capability of particle manipulation in Fluorinert has been observed in our preliminary experiments. The device has been tested in water as well. However, bubble formation coming from electrolysis is the major problem encountered at current stage. Several solutions to prevent electrolysis such as driving actuator with modulated AC signals are undertaking in our research group.

CONCLUSIONS

A lobster-sniffing inspired actuator for micro-objects manipulation in liquid environment using electrostatic actuation is proposed. Structure analyses, electromechanical simulation and the simulation model which investigates the interaction between the biomimic actuator and their surrounding fluid are carried out to acquire design criteria. The feasibility and functionality of micro-object manipulation by varying local fluid field is experimentally observed. Since our device manipulates particle via controlling the fluid surrounding the targeted particle, it is a potential tool for the applications of non-contact and non-invasive micro-manipulation in liquid environment.

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