A DC DRIVE ELECTROSTATIC COMB ACTUATOR BASED ON SELF-EXCITED VIBRATION

Yangsheng Zhu[1], Xiaojun Yan[1,3,4], Mingjing Qi[1,2], Zhiwei Liu[1], Xiaoyong Zhang[1,4], and Liwei Lin[2]
[1]School of Energy and Power Engineering, Beihang University, Beijing, CHINA
[2]Mechanical Engineering Department, University of California at Berkeley, USA
[3]Collaborative Innovation Center of Advanced Aero-Engine, Beijing, CHINA
[4]National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, CHINA

ABSTRACT

We report a novel electrostatic comb actuator for linear motion output by electrostatically induced self-vibration under a direct-current (DC) power supply. The comb actuator contains 4 pairs of electrodes and has a total mass of 60 mg. It can achieve output displacement with amplitude range from 0.9 mm to1.4 mm at a vibration frequency of about 220 Hz. The power density can reach 32.04 W/kg, which is 4 times of the previous actuators with a single-pair of electrodes. The comb actuator could open up new directions for electrostatic force utilization in millimeter scale.

INTRODUCTION

Nowadays, actuators, especially linear actuators with light weight, high output force and large displacement, are in urgent demand in the fields such as micro robotics, and micromechanical systems [1]. Piezoelectric actuators [1, 2], shape memory alloy (SMA) actuators [3, 4] and electrostatic actuators [5, 6] have been designed and utilized for such applications.

The traditional electrostatic actuators are mainly comb actuators which works under DC polarization voltage and AC voltage [7, 8]. These actuators usually consist of two conductive comb structures, one is fixed and the other is connected to a spring which makes sure that the two combs never touch. This type of comb actuators usually operates at micrometer or nanometer scale and are fabricated though surface micromachining, and they have been widely used in the fields of resonators, electromechanical filters, optical shutters and voltmeters. However, the output power of traditional electrostatic comb actuators is limited in millimeter scale and they can hardly meet the actuation requirement of micro robotics.

Recently, a novel electrostatic actuator has been reported based on the principle of self-excited vibration under an applied DC voltage [6, 9]. The actuator has been used to realize the vertical takeoff of artificial insect wings [10] and drive an insect-size crawling robot [11]. This new type of electrostatic actuator can output large displacement in millimeter-scale or submillimeter-scale. Since the actuator operates under only DC voltage, it is much easier for future integrations with power modules. However, due to the structural limitation, the output power of the actuator with single pair of electrodes still needs to be enhanced for future application in micro robotics.

Here, by combining comb structure design and self-excited vibration principle, we present a novel self-excited electrostatic comb actuator. The actuator consists of four pairs of fixed comb electrodes and a vibrating comb-figure cantilever assembly. A prototype actuator is designed and fabricated through laser cutting and manual assembly to verify the concept of the DC drive electrostatic comb actuator and to demonstrate its advantages of large displacement and high power density.

DESIGN AND FABRICATION

The comb actuator is designed by combining the advantage of the traditional comb drive structure and the self-excited vibration principle reported previously [6]. Figure 1a shows the schematic diagram of the comb actuator to illustrate its working principle. The prototype consists of four cell structures. All the cell structures are similar to the configuration of the previous actuator presented in [6], which consists of a single pair of electrodes and a vibrating beam. For the previous actuator, the cantilever beam is placed in the middle of the electrodes. When the DC voltage is applied to the two electrodes, the cantilever beam will be excited into vibration and impact the positive and negative electrodes in turns.

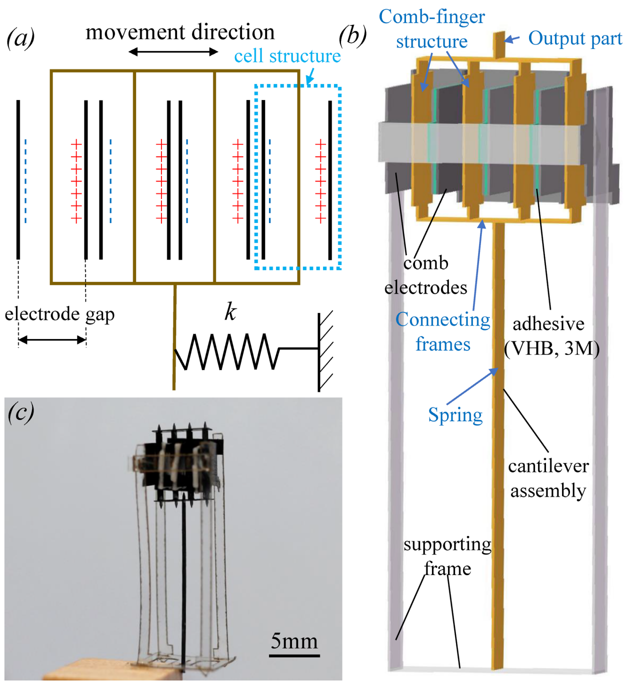

Figure 1: (a) schematic diagram of the comb actuator to demonstrate its working principle. (b) 3D model and (c) an optical photo of the electrostatic comb actuator.

In the comb drive design of this investigation, the cantilever assembly consists of a spring, two connecting frames, a comb-finger structure and the output part as shown in Figure 1b. The spring mainly provides the restoring force during the vibration. The comb-figure structure is made of four identical plates and it is subjected to the electrostatic force in the cell unit. In other words, the electrostatic force and restoring force are provided by electrodes and the spring at the fixed end of the cantilever assembly respectively.

To achieve light weight and high strength of the comb actuator, the different parts of the actuator is fabricated with different materials. In the prototype shown in Figure 1c, the spring is made of a 100 μm-thick, 14 mm-long and 1 mm-wide carbon fiber plate to provide restoring force. The comb-finger is also made of carbon fiber plate which is 30 μm in thickness with the area of 3 mm × 4 mm for light weight. Based on the self-excited vibration principle, when a high DC voltage is applied to the fixed comb electrodes, the cantilever assembly will be excited into vibration.

Figure 2 describes the details of the fabrication and assembly process. The prototype comb actuator is 22 mm-long with a total mass of 60 mg. The electrodes and the cantilever assembly are mainly made of carbon fiber plates (Toray company) by using a laser cutting machine (Planck PLS-20B, power 20 W, wave length 1064 nm, China) to achieve the designed shape. The four pairs of electrodes are fixed together by double-side VHB adhesive from 3M company as well as for insulation. The supporting frame is made of insulating material, such as plastic plate (100 μm in thickness, PET, Nalifilm company). All the components are glued together manually and mounting grooves and flanges are designed to improve the installation accuracy.

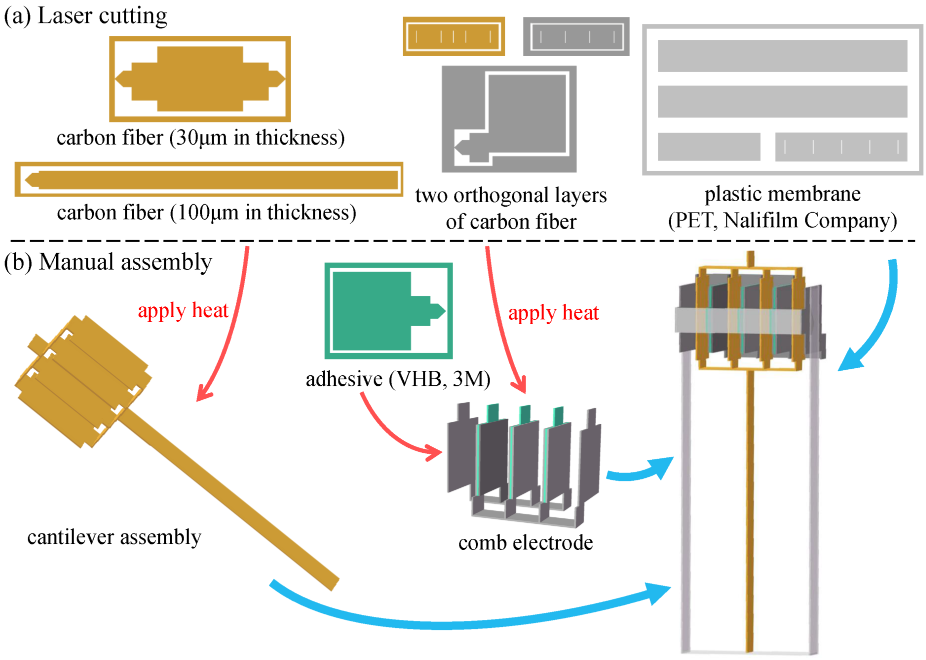

Figure 2: Fabrication and assembly process of the electrostatic comb actuator. The prototype comb actuator has a total mass of 60 mg by using lightweight materials.

EXPERIMENTAL RESULTS

Figure 3a shows the test system which is setup to observe and record the operations of the fabricated prototype comb actuator. As shown in the embedded circuit diagram in Figure 3a, a DC power source provides high DC voltage to the electrodes and a high precision electrometer acts as an ammeter to measure the current flowing through the circuit. A high-speed camera is used to capture the vibration process of the cantilever assembly and the vibration frequency can be obtained by analyzing

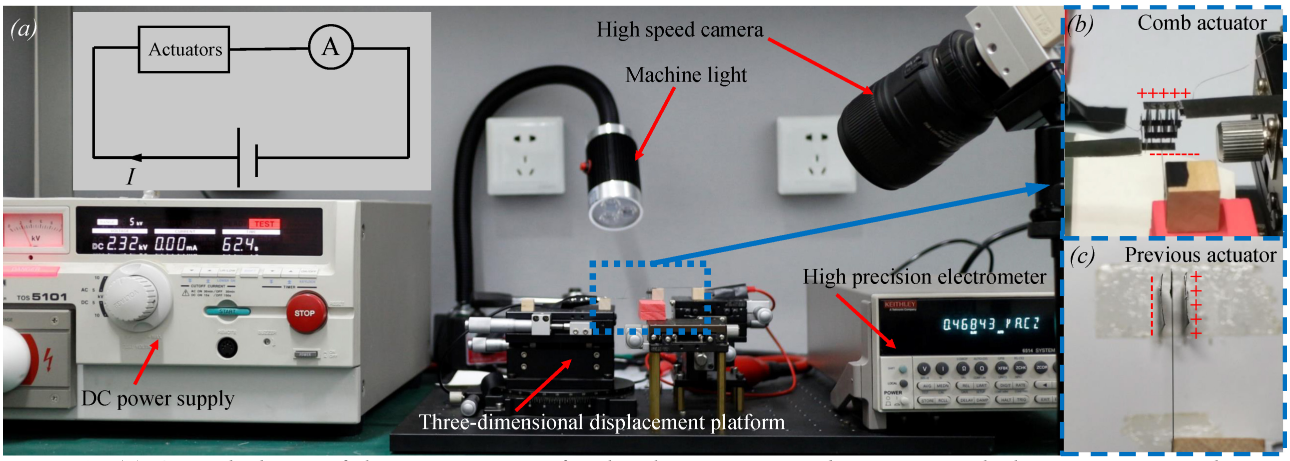

Figure 3: (a) Optical photos of the testing system for the electrostatic comb actuator with the testing circuit diagram embedded. (b) Enlarge diagram of the comb actuator. (c) Photo of the previous actuator with single pair of electrodes.

the high speed images. A machine light is set to provide enough light for high-speed camera.

In this test, except for the applied DC voltage, the gap distance between the electrodes is also one of the influence factors that should be considered. As shown in Figure 3b, the gap distance between the positive and negative electrodes can be adjusted by using a three-dimensional displacement platform. Based on the vibration principle, the output displacement of the cantilever assembly is equal to the gap distance between the electrodes (0.9-1.4 mm in this test). Figure 3c shows the previously developed actuator which can drive the crawling robot to move forward [11]. The output performance of the previous actuator is also measured as a comparison. The cantilever beam of this actuator is 16 mm long, which is same as the length of the spring in the comb actuator.

The experimental results of the tests are plotted in Figure 4. For comb actuator, higher applied DC voltage results in more charge transfer when the cantilever assembly impacts the electrodes, which increases the equivalent current as well as input power. The vibration frequency of the cantilever assembly is relatively stable at 220 Hz under different DC voltages. The test results demonstrate that the distance between the electrodes also has influence on the equivalent current and input power. When the electrode gap distance becomes too small or too large, the cantilever assembly cannot even be excited into vibration at relatively low voltages. This can be explained as follows. When the gap distance increases to a certain value, the electric field intensity decays and cannot provide enough electrostatic force to excite the vibration. If the gap distance is too small, the processing and assembly error will also affect the vibration of the cantilever assembly. In spite of the unavoidable measurement errors, we can still find out the gap distance of 1.2 mm is the optimal distance for the prototype comb actuator from the data plots in Figure 4a and 4c.

Since the comb actuator operates without workload, it is not practical to evaluate the output power. When the power of dissipation is constant, the output power is determined by the input power. In this investigation, the input power is chosen as an evaluation index for the actuator's performance, which is given by:

$$P_{in} = UI \tag{1}$$

where U is the applied DC voltage and I is the equivalent current. With the increase of the DC voltage, the input power increases dramatically and can reach 1.9 mW when the gap distance between the electrodes is 1.2 mm.

Compared with the previous actuator with one pair of electrodes used in the crawling robot, the vibration frequency as well as input power of the comb actuator both demonstrate significant enchantment. We define the input power density as the evaluation standard to eliminate the effect of the actuators' mass. The input power density can be calculated as:

$$\omega = \frac{P_{in}}{m} \tag{2}$$

where m is the total mass of actuator. For the prototype comb actuator, the input power density is up to 32.04 W/kg, which is close to 4 times of that of the previous actuator at about 8.47 W/kg. In the future, the input power density of the comb actuator can be further enhanced by optimizing the structure design and choosing more effective fabrication method like high-precision 3D printing to reduce the total weight of actuator.

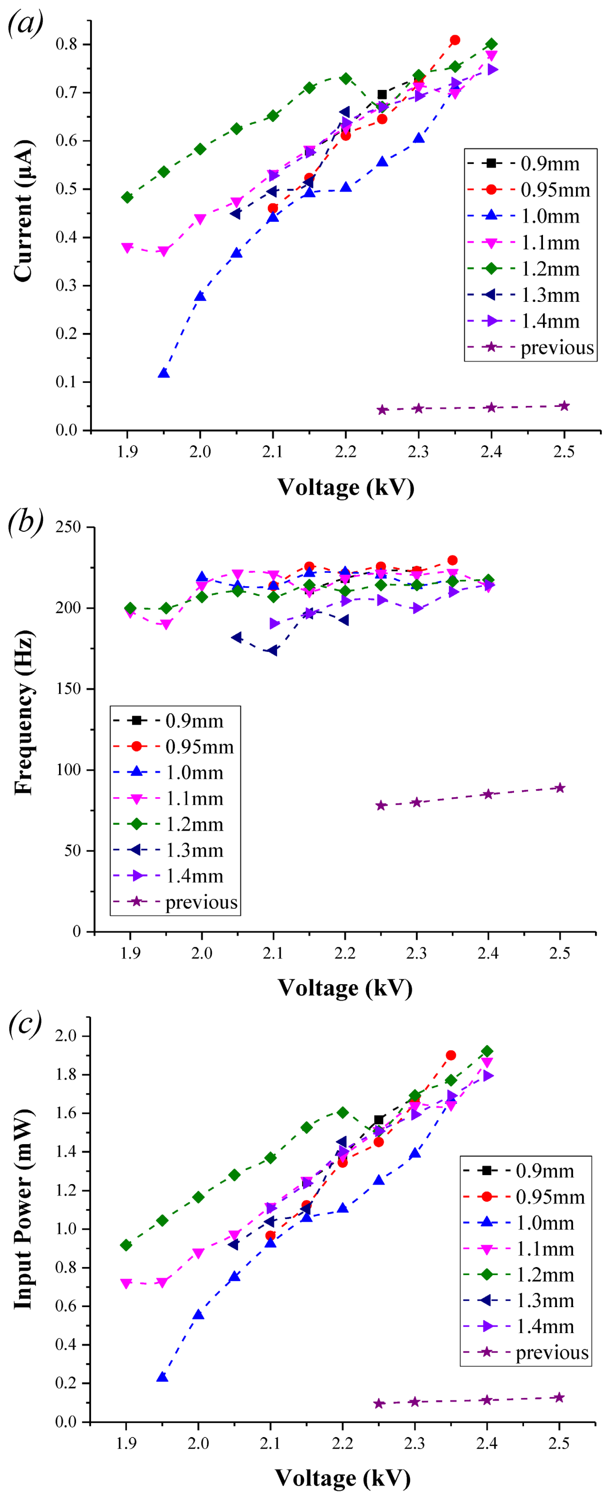

Figure 4: Experimental comparison of electrostatic comb actuators with different electrode gap distances (0.9-1.4 mm) and previous actuator with single pair of electrodes (purple star symbols). (a) Larger equivalent current with higher applied voltage. (b) Vibration frequency remains almost stable with increased applied voltage. (c) Larger input power with higher applied voltage.

CONCLUSIONS

This paper presents a DC drive electrostatic comb actuator based on self-excited vibration principle. By using laser cutting and manual assembly, a prototype is fabricated and tested to verify the design. The test results indicate that the frequency of the comb structure remains almost stable at 220 Hz while the current and input power increase dramatically with increased DC voltage. Under an applied DC voltage of 2.4 kV, the comb actuator can achieve an input power density of 32 W/kg, which is close to 4 times as high as that of the previously developed electrostatic actuator. Future work aims at further improving the fabrication accuracy and enhancing the power density of the comb actuator for the application in micro robotics.

ACKNOWLEDGEMENTS

This work is supported by China Scholarship Council (CSC, 201506020261), National Natural Science Foundation of China (Grant No. 11602010 and No. 51505018), and the 111 Project (Grant No. B08009).

REFERENCES

[1] R. J. Wood, E. Steltz, and R. S. Fearing, "Optimal energy density piezoelectric bending actuators," *Sens. Actuator A-Phys,* vol. 119, pp. 476-488, 2005.

[2] K. L. Hoffman, and R. J. Wood, "Myriapod-like ambulation of a segmented microrobot," *Auton. Robot,* vol. 31, pp. 103-114, 2011.

[3] A. M. Hoover, E. Steltz, and R. S. Fearing, "RoACH: An autonomous 2.4g crawling hexapod robot," in *2008 Ieee/Rsj International Conference on Robots and Intelligent Systems*, 2008, pp. 26-33.

[4] J. S. Koh, E. Yang, G. P. Jung *et al.*, "BIOMECHANICS. Jumping on water: Surface tension-dominated jumping of water striders and robotic insects," *Science,* vol. 349, pp. 517, 2015.

[5] R. Yeh, S. Hollar, and K. S. J. Pister, "Single mask, large force, and large displacement electrostatic linear inchworm motors," *J. Microelectromech. Syst.,* vol. 11, pp. 330-336, 2002.

[6] X. Yan, M. Qi, and L. Lin, "An autonomous impact resonator with metal beam between a pair of parallel-plate electrodes," *Sens. Actuator A-Phys,* vol. 199, pp. 366-371, 2013.

[7] W. C. Tang, T.-C. H. Nguyen, and R. T. Howe, "Laterally Driven Polysilicon Resonant Microstructures," *Sensors and Actuators,* vol. 20, pp. 25-32, 1989.

[8] R. Legtenberg, A. W. Groeneveld, and M. Elwenspoek, "Comb-drive actuators for large displacements," *J. Micromech. Microeng.,* vol. 6, pp. 320, 1996.

[9] X. Yan, M. Qi, X. Wu *et al.*, "Electrostatic cantilever resonators under a double-sided pull–pull drive scheme," *J. Micromech. Microeng.,* vol. 24, pp. 035004, 2014.

[10] X. Yan, M. Qi, and L. Lin "Self-lifting artificial insect wings via electrostatic flapping actuators," in *Proc. IEEE Int. Conf. MEMS*, 2015, pp. 22-25.

[11] M. Qi, Y. Zhu, Z. Liu *et al.* "A fast-moving electrostatic crawling insect," in *Proc. IEEE Int. Conf. MEMS*, 2017, pp. 761-764.

CONTACT

* Xiaojun Yan, tel and fax: +86-10-82316356; yanxiaojun@buaa.edu.cn