



Design of the Piezoelectric Actuator with Double Driving Tips

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Abstract: The general operation of a piezoelectric ultrasonic resonant actuator is to convert the cyclic motion of the piezoelectric plate to a linear motion at the rotor or slider. The conventional piezoelectric ultrasonic actuator has only one stator tip to impart both the contact (normal) and driving (tangential) force on the rotor or slider. Since the rotor/slider is driven through friction, the only one stator tip design will result in lower output torques. In theory, a piezoelectric ultrasonic actuator with more stator tips will have larger output torques. However, it is difficult to design a piezoelectric actuator with multiple stator tips with synchronous cyclic motion. In this paper, the design and simulation of a novel piezoelectric actuator with multiple stator tips are presented. The accomplishment of this study is to reduce the motion difference between two different stator tips on the piezoelectric ultrasonic actuator. The Taguchi method was used to find out the optimal dimensions of the piezoelectric plate and the result shows the motion difference between two different stator tips was reduced from $19\mu\text{m}$ to $0.03\mu\text{m}$ in the X-direction and from $9\mu\text{m}$ to $0.18\mu\text{m}$ in the Y-direction.

Keywords: Ultrasonic Resonant Actuator; Piezoelectric Plate; Multiple Driving Tips

Introduction

Piezoelectric ultrasonic resonant actuators have been widely used in industry. This is due to their outstanding characteristics such as large output torques, no gearbox or brake mechanism required, no bearings, quick response, no backlash, high positioning resolution, absence of magnetic fields, simple structure, linear direct driving, small volume, low power consumption and high positioning accuracy. More and more applications of the piezoelectric ultrasonic resonant actuator have been applied in daily life such as in atomizing devices, medical micro-nebulizers and the zooming/image stabilization system in digital cameras. A new design of micro-nebulizer, integrating a piezoelectric actuator, micro-nozzle plate, and the cavity of a micro pump to achieve a high-quality atomizing effect was presented in 2008 [1, 2]. Another cymbal-shaped high power

micro-actuator for nebulizer application was presented in 2010. The ring-type piezoelectric plate and cymbal-shaped micro nozzle plate were used in medical micro-nebulizers. The cymbal-shaped feature of the micro nozzle plate could focus energy onto its center and induce a large force, which provided the cymbal-shaped micro-actuator with high power to spray medical solutions of high-viscosity resulting in the production of ultra-fine droplets and increases in the atomization rate [3, 4]. In addition, some piezoelectric motors also could be used to move a lens and image sensors in order to create a zooming function in digital cameras. A piezoelectric element based smooth impact drive mechanism (SIDM) was presented in 2004 [5]. The mechanism was a linear actuator that utilized the rapid expansion or contraction of a piezoelectric element and the friction created between a rod attached to the piezoelectric element and a mobile body. The proposed actuator, small and capable of being driven with high



precision, may be used to swing the image sensor in image stabilization systems so as to compensate for handshake [6].

Many kinds of piezoelectric ultrasonic resonant actuator have been developed for certain applications in recent years. However, the core characteristics required of actuators are the same. Actuators at this scale require high output forces, accuracy, low response times, a simple design and simple operation [7]. Piezoelectric ultrasonic motors can be divided into two categories: standing wave ultrasonic motors (SWUM) and traveling wave ultrasonic motors (TWUM). The key differentiation in the design of piezoelectric ultrasonic actuators is the method by which the stator converts the motion of the piezoelectric elements to the elliptical stator tip motion. The SWUM rely on standing waves to produce motion and they are simple to design and build. The TWUM produce motion by means of the superposition of standing waves in the stator. A single-mode piezoelectric actuator for ultrasonic linear motors was developed in 2005 [8]. The friction element, as the driving tip, was attached at the midpoint of the long edge of the piezoelectric plate. A two-dimensional standing wave would occur at the midpoint of the long edge of the piezoelectric plate when the actuator was excited asymmetrically. The superposition of the two-dimension standing wave would produce a cyclic motion. With a proper preload, the piezoelectric actuator would push the linear slider. Since the slider is driven through friction, the only one stator tip design will result in lower output torques. This will limit the application field of this kind of piezoelectric actuator. In theory, a piezoelectric ultrasonic actuator with more stator tips will produce larger output torques. However, it is difficult to design a piezoelectric actuator with multiple stators which have synchronous cyclic motion. If the motion difference between two different stator tips could be reduced to zero, it would be possible to build a large-output piezoelectric actuator with multiple driving tips.

Piezoelectric Actuator with Multiple Driving Tips

The conventional piezoelectric actuator with single driving tips and the linear stage driven by it are shown as Figure 1. The actuator consists of a piezoelectric plate which is polarized in the Z direction and a friction

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element (driving tip) attached on the long edge of the piezoelectric plate. The electrodes are on the large surfaces (X-Y planes) of the plate. There are two exciter electrodes on the front surface and each electrode covers one half of the front surface. The rear surface has only one electrode that serves as a common drain. There is only one driving tip attached on the long edge of the piezoelectric plate. The basic design concepts of the novel piezoelectric actuator with multiple driving tips and the linear stage driven by it are shown as Figure 2. Compared with the conventional piezoelectric actuator, there are two driving tips attached on the long edge of the piezoelectric plate.

The finite-element method simulation of the piezoelectric actuator with single driving tip and the piezoelectric actuator with multiple driving tips are shown as Figure 3 (a) and Figure 3 (b) respectively. The actuator is excited (active) by one of the electrodes on the front surface, and the other front electrode is left floating (free). The piezoelectric actuator was excited with higher frequency to increase the number of the waves on the long edge of the piezoelectric plate. The vibration mode of the piezoelectric actuator is shown as Figure 4. The P1 and P2 are the locations where the driving tips attach. From the simulation results, it is found that the motion trajectories of P1 and P2 are elliptical trajectories with different sizes. However, to make a piezoelectric actuator with better operating characteristics, these two driving tips should have the same cyclic motion. Thus, it is very important to design a piezoelectric actuator with multiple stator tips which have synchronous cyclic motion.

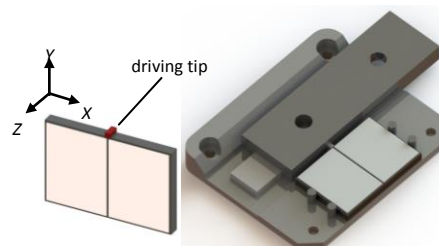


Figure 1. The linear stage driven by the piezoelectric actuator with single driving tip.

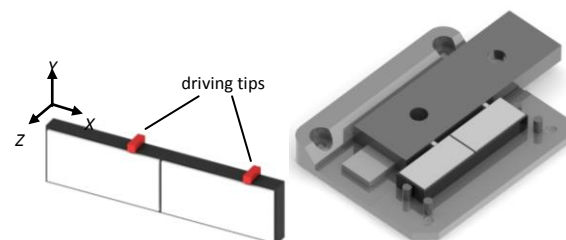


Figure 2. The linear stage driven by the piezoelectric actuator with multiple driving tips.

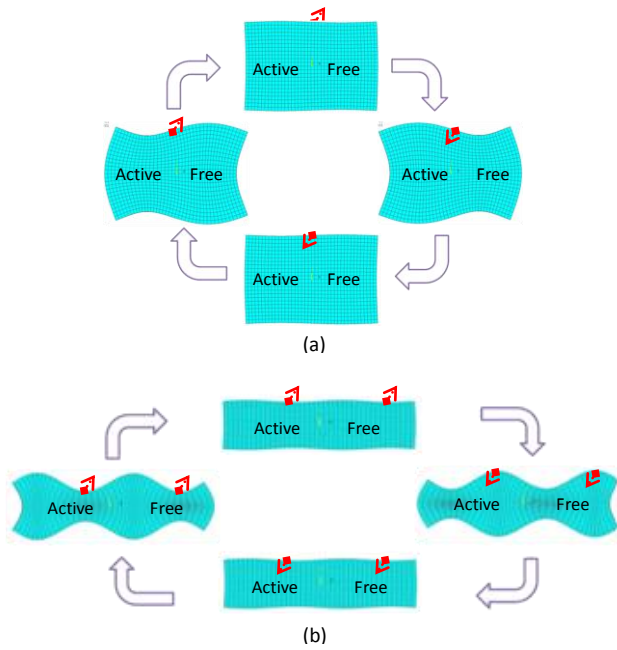


Figure 3. (a)The actuator motion in Figure1. (b)The actuator motion in Figure2.

Simulation Experiment

Design of Experiments

The Taguchi method, a kind of experimental design, is a statistical method developed by Genichi Taguchi to improve the quality of a product or a manufacturing process. It has been used to improve the quality of products for a long time. It usually uses the lowest cost to obtain the best quality by utilizing tools such as *S/N* ratio and orthogonal arrays. Using this method, the product quality is insensitive to variance caused by “noise factors” and an optimal parameter combination can be obtained. In this study, the Taguchi method is used to find out the optimal dimensions of the piezoelectric actuator which has the smallest motion difference between two different stator tips on the piezoelectric plate. By conducting a simulation experiment [9], the optimal parameter combination can be obtained.

In this study, “motion difference between two different stator tips on the piezoelectric plate” is chosen to be the quality characteristics. Through brainstorming in the early design stage, all possible design parameters that affect the “motion difference between two different stator tips on the piezoelectric plate” were considered, as shown in Figure 5. The four chosen control factors and their levels for the experiment are shown in Table 1. An *L18* array was used to set the parameter optimization experiment levels.

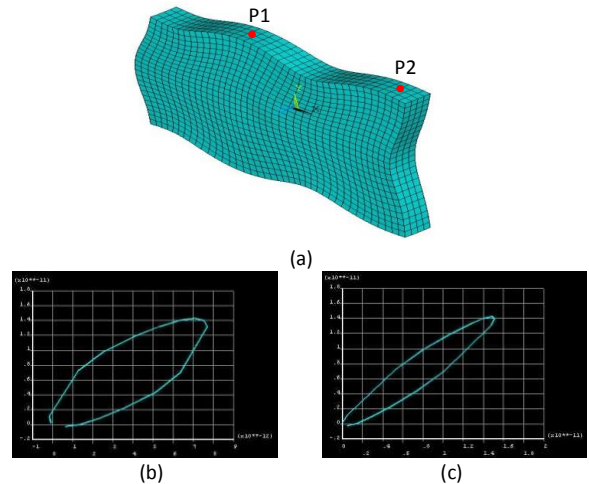


Figure 4. (a)The vibration mode of piezoelectric actuator. (b)The motion trajectory of P1. (c) The motion trajectory of P2.

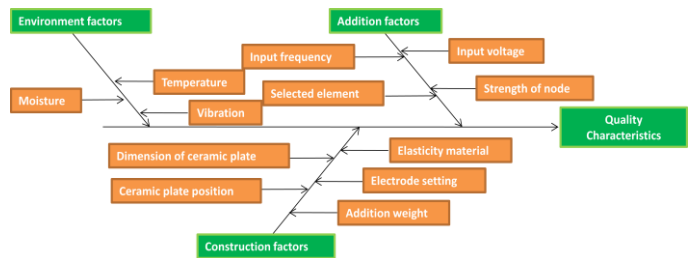


Figure 5. The fish bone diagram of the design parameters.

Table 1. The control factors and levels table (original design).

Factor\Level	Level 1	Level 2	Level 3
Input voltage	5 volt	10 volt	20 volt
Length	12 mm	16 mm	20 mm
Width	4 mm	8 mm	12 mm
Thickness	1 mm	1.5 mm	2 mm

Experiment Results

In this study, the quality characteristic is smaller-is-better. We seek to minimize the motion difference between two different stator tips on the piezoelectric plate to attain a piezoelectric actuator with multiple stator tips which have synchronous cyclic motion. The smaller-the-better *S/N* ratio is based on the small-the-better loss function. The derivation of the smaller-the-better type *S/N* ratio is based on the following ideas: (1) quality characteristics or response values are continuous and nonnegative, (2) the desired value of the response is zero, and (3) the goal is simply to minimize the mean and variance simultaneously. The smaller-the-better *S/N* ratio is defined by:

$$S / N_{STB} = -10 \log(S^2 + \bar{y}^2) = -10 \log(MSD). \quad (1)$$

S: standard deviation, \bar{y} : mean value of experiment results, *MSD*: mean square deviation.

The simulation experiment results of quality characteristics and S/N ratios are listed in Table 2. Δx and Δy are the quality characteristics in the X-direction and Y-direction respectively. S/N_x and S/N_y are the S/N ratio of the quality characteristics. The factor effects responses are listed in Table 3 and Table 4. The factor effects plots are shown as Figure 6 and Figure 7.

Table 2. Experiment results (unit: m).

Exp.	Δx	Δy	S/N _x	S/N _y
1	4.70E-07	3.43E-06	126.558	109.294
2	6.01E-09	2.50E-09	164.419	172.041
3	4.10E-06	7.68E-06	107.744	102.298
4	6.00E-05	3.00E-04	84.437	70.458
5	1.46E-08	6.25E-09	156.713	164.082
6	8.50E-07	9.50E-07	121.412	120.446
7	1.90E-05	9.00E-06	94.425	100.915
8	5.75E-06	2.30E-05	104.807	92.765
9	3.00E-08	1.88E-08	150.458	154.540
10	3.60E-06	6.70E-06	108.874	103.479
11	2.00E-08	2.00E-07	153.979	133.979
12	3.44E-07	2.00E-06	129.275	113.979
13	4.90E-08	7.25E-05	146.196	82.793
14	1.81E-05	5.99E-05	94.834	84.451
15	6.38E-09	4.00E-08	163.910	147.959
16	2.00E-06	3.00E-07	113.979	130.458
17	2.80E-08	1.83E-07	151.057	134.775
18	6.00E-06	4.31E-05	104.437	87.305

Table 3. The S/N_x ratio response table.

Factors	Input voltage	Length	Width	Thickness
Levels	(B)	(C)	(D)	(E)
1	131.81	112.41	138.40	115.94
2	127.92	137.63	132.58	126.80
3	119.86	129.54	108.61	136.84

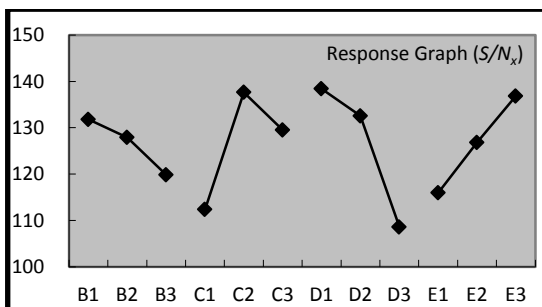


Figure 6. The factor effects response plot of S/N_x.

Table 4. The S/N_y ratio response table.

Factors	Input voltage	Length	Width	Thickness
Levels	(B)	(C)	(D)	(E)
1	122.51	99.57	125.17	106.07
2	111.70	130.35	120.19	121.28
3	116.79	121.09	105.65	123.66

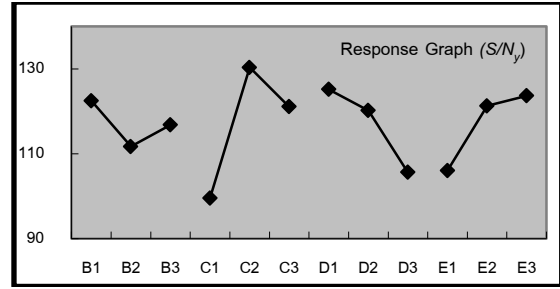


Figure 7. The factor effects response plot of S/N_y.

After the parameter optimization experiments, the optimal assembly of control factors and levels in the X-direction and Y-direction are both B1 C2 D1 E3 as seen in the S/N ratio response table. Among the factors and levels, the three factors C, D, E are considered as the significant factors since the effect of factor B is smaller than others. The second level of factor C is 16 mm (the length of piezoelectric plate). The first level of Factor D is 4 mm (the width of piezoelectric plate). The third level of Factor E is 2 mm (the thickness of piezoelectric plate). Therefore, the optimal assembly of control factors C, D, E is C2 D1 E3, and the factor B is still set as the original level.

Confirmation Experiments

The optimal assembly of control factors and levels of all the designs is B3 C2 D1 E3. The predicted results (S/N ratio) of the optimal assembly of control factors are:

$$\begin{aligned} \eta_{x-predict} &= \bar{\eta}_x + (\eta_{xC2} - \bar{\eta}_x) + (\eta_{xD1} - \bar{\eta}_x) + (\eta_{xE3} - \bar{\eta}_x) \\ &= \eta_{xC2} + \eta_{xD1} + \eta_{xE3} - 2 \times \bar{\eta}_x \quad (2) \\ &= 137.63 + 138.40 + 136.84 - 2 \times 126.53 \\ &= 159.81 \end{aligned}$$

$$\begin{aligned} \eta_{y-predict} &= \bar{\eta}_y + (\eta_{yB2} - \bar{\eta}_y) + (\eta_{yD1} - \bar{\eta}_y) + (\eta_{yE3} - \bar{\eta}_y) \\ &= \eta_{yC2} + \eta_{yD1} + \eta_{yE3} - 2 \times \bar{\eta}_y \quad (3) \\ &= 130.35 + 125.17 + 123.66 - 2 \times 177.00 \\ &= 145.18 \end{aligned}$$

A confirmation experiment, using FEM simulation, is also carried out in this study. The vibration mode of the piezoelectric actuator with multiple driving tips is shown as Figure 8 (a). The motion difference between P1 and P2 in the X-direction is shown as Figure 8 (b).

Table 5. Confirmation experiment table.

	Quality Characteristics	S/N ratio	
		Experiment	Predicted
X-Original	1.90E-05	94.43	107.88
X-Optimal	2.80E-08	151.06	159.81
Y-Original	9.00E-06	100.92	91.83
Y-Optimal	1.83E-07	134.78	145.18

The predicted results and experiment results are all listed in Table 5. After carrying out the simulation and prediction of optimum performance, the motion difference between the two different stator tips on the piezoelectric ultrasonic actuator in the X-direction is from 19 μm to 0.03 μm and the motion difference in the Y-direction is from 9 μm to 0.18 μm . The quality characteristics are improved by 18.97 μm and 8.82 μm respectively.

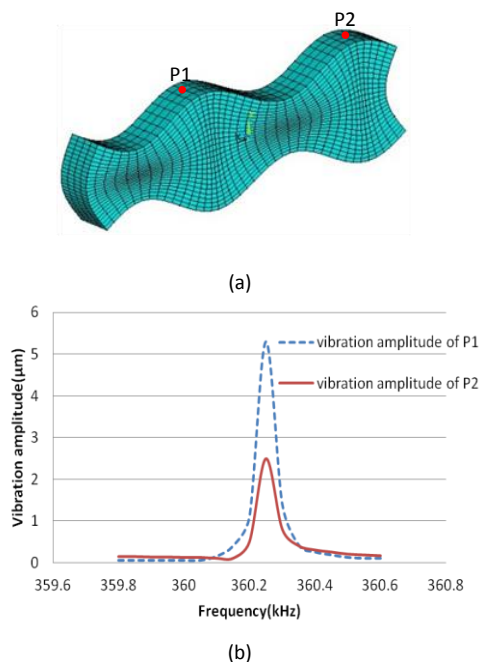


Figure 8. (a)The Confirmation experiment simulation. (b)The motion difference between P1 and P2 in the X-direction.

Conclusion

In this paper, the design and simulation of a novel piezoelectric actuator with multiple stator tips is presented. The main purpose of this study is to find the optimal dimensions of the piezoelectric plate which have the smallest motion difference between two different stator tips on the piezoelectric ultrasonic actuator. From the simulation experiment results, the main factor inflecting the motion difference between two different stator tips on the piezoelectric ultrasonic actuator is the length of the piezoelectric plate, and the optimal dimensions of the piezoelectric plate are 16×4×2 mm. The motion difference between the two different stator tips on the piezoelectric ultrasonic actuator in the X-direction is from 19 μm to 0.03 μm and the motion difference in the Y-direction is from 9 μm to 0.18 μm . In the future, a piezoelectric actuator driven stage with multiple driving tips will be developed, and some performances of the stage such as output torque and output velocity will be tested. More topics relating to this novel piezoelectric actuator with multiple stator tips will also be investigated.

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