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Sensors and Actuators A 118 (2005) 285–291

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Development of a novel high precision piezoelectric linear stepper actuator

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Received 27 July 2004; accepted 31 July 2004

Abstract

A novel linear stepper piezoelectric actuator is reported in this paper. We designed the configuration of the actuator and fabricated its prototype. A testing system was set up to examine its dynamic characteristic. It has been found that the actuator moves in stepping mode under lower pulse frequency and achieves the highest velocity and the longest range when the duration of high level is 1 ms. The new actuator has a displacement resolution of 0.1 μm and a maximum velocity of 0.6 mm/s. Its load may be 200 g and its range may be several centimeters. Besides, it also has a simple configuration and is easy to be controlled. A high precision positioning system can be achieved with it.

Keywords: Actuator; Piezomotor; Positioning system; Stepper motor

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1. Introduction

Piezoelectric motor is a focus in the domain of high precision positioning technology in recent years. Compared to electromagnetic motor, piezomotor has many advantages, such as simple configuration, small size, high resolution, good controllability, environment immunity and so on. There exist two types of piezomotor. One is rotary motor, which rotates an angle under the driving of a pulse, the other is stepper motor, which is driven to move a step by a pulse. With the development of microelectronic technology, communication technology, nanotechnology and computer technology, the performance of high resolution positioning stepper piezomotor has been improved greatly.

The first piezomotor, the type of which is rotary, was fabricated by V.V. Lavrinenko and his colleagues in 1964 at the Kiev Polytechnical Institute. From 1969 to 1990, main researches about piezomotor in the former Soviet Union had been finished in the Research Center 'Vibrotechnika' at the Kaunas University of Technology, Lithuania, Kiev Polytechnical Institute, Ukraine and Leningrad Polytechnical Institute, Russia [1]. Burleigh Company applied the first U.S.A. patent for piezomotor called "Inchworm" in 1975. This motor was named "Inchworm" because it simulated inchworm's movement [2].

The principles of many piezoelectric motors originated from the "Inchworm". For such kind of motors, there are three piezoelectric ceramics stacks and a guideway at least. Usually, the middle stack is used as actuator while the other two are used as clamps. By the clamping of the guideway by two clamps in time-sharing manner and by the extending and the withdrawing of the actuator, the motor can move forward or backward in steps [3–8].

"Traveling wave motor" is another kind of piezomotor. The motor consists of piezoelectric ceramic stacks and elastic material plank, which are coupled together. The piezoelectric stacks produce traveling waves or standing waves on the elastic material plank. The slider on the plank can be driven to move by the friction originated from those waves [9,10]. Morita et al. reported a micro-ultrasonic motor [11]. Their motor is composed of a stator transducer, a rotor and a preload mechanism. The rotor is driven by applying ±90° phase electric sources. In the same manner as traveling wave

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doi:10.1016/j.sna.2004.07.016

type piezomotor, the rotor turns through *friction*.This motor has an outer diameter of 1.4 mm and a length of 5.0mm. Its maximum output torque is 0.67 μN m.

"Frog-jumping motor" named because its movement is imitative of the frog's jump was proposed by Higuchi et al. [12]. The major part of the motor includes two masses and an in-between piezoelectric stack. One mass is bigger and heavier than the other. A special pulse is needed for driving the motor. The piezoelectric stack can extend slowly and withdraw quickly so that the motor can be driven to move by the inertia of the masses. This kind of motor is easy to be miniaturized and may find applications in microsystem.

Petit et al. advanced a new structure of piezomotor using a flextensional coupler [13]. Its major part includes two longitudinal actuators and a shell of elliptical section. The elliptic shell is the mechanical coupler, which is deformed by the actuators. The motor works based on two modes: a flexion mode, which occurs when the two actuators are electrically supplied in phase and thus a normal component of vibration U_z is generated, and a translation mode, which occurs when an opposite phase supply of the two actuator leads to a simple translation of the shell and a tangential component of vibration U_θ induced. Elliptic motion of the shell surface is obtained when a supply with 90° difference of phase applied on the actuators. Although this motor has a simple structure and its load capacity is high, it lacks compactness.

An atomic resolution and millimeter range piezoelectric motor was reported recently. Its range can be 1.9 mm and its load capacity is 0.03 N. This kind of motor has the size as small as a match and a very high resolution, but its load capacity is too small and its range is short [14].

Although the existing motors have exhibited excellent performance, some shortcomings still need to be overcome. For instance, some inchworm type motors have high mechanical stiffness and resolution but their ranges are too short and they are also difficult to be controlled [3–8]. Frog-jumping motor has a simple structure and is easy to be miniaturized but its driving pulse is difficult to be generated [12]. Some motors have small size but their load capacity is too small [11,14], and some motors have both too small load capacity and too big size so that they cannot be used in microsystem [9,10,13].

In this paper, we report the fabrication of a novel stepper actuator. It has a simple configuration, a long range, a rapid velocity and a high resolution and may be applied in high precision positioning closed loop control system.

2. Fabrication of the motor and its principle

Piezoelectric ceramic rings and copper-ring electrodes were linked together by the variable amplitude lever and the fastener as shown in Fig. 1. A screw with the length of about 10 cm linking up with the fastener is used to keep the movement direction of the actuator. A spring is around the screw. All of these are fastened with a guideway through a sleeve. A piece of polytetrafluoroethylene (PTFE) film is used between the sleeve and the screw to reduce the friction. The variable amplitude lever touches a slider with the mass of 200 g. The spring is compressed by the sleeve and variable amplitude lever. A grating is fastened on the slider to test its displacements. Another piece of PTFE film is used between the slider and the guideway. A copper plank is inserted between the slider and the mirror-polished upper surface of the guideway. The copper plank is curved and used to adjust the friction between the slider and the guideway so that the actuator keep still before the expansion of piezoelectric ceramics and moves once the ceramics expand. Pulse waveform is used to apply the electric field on the piezoelectric ceramics and its amplitude and frequency may be changed successively. There are not clamps in this kind of actuator, so the control, friction and quiver noise problems of the clamps disappear and its structure is simple. The configuration of the motor is shown in Fig. 2.

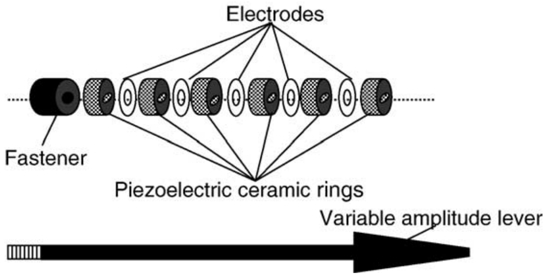

Fig. 1. The structure of the actuator.

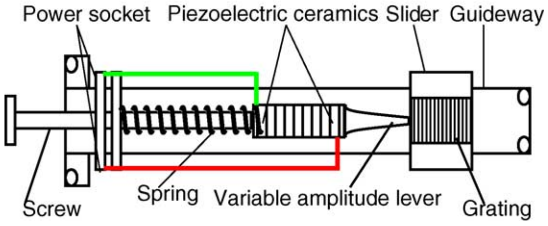

Fig. 2. The configuration of the new stepper actuator.

The movement principle of the actuator is shown schematically in Fig. 3 and explained as follows. When a high level comes, the piezoelectric ceramics expand and drive the slider to move a step. At the same time, the spring is compressed to save energy. When a low level comes, the deformation of the ceramics disappears and the spring drives the actuator to move and impact the slider. Afterwards, the actuator and the

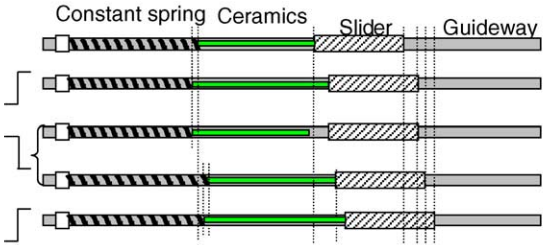

Fig. 3. The movement principle of the novel actuator.

slider will move together for a little distance and then stop because the impact is nonelastic. The friction and the elasticity keep the system still to wait for the next pulse waveform. While the successive pulses are applied, the actuator and accordingly the slider or other load can move a long distance. The load may be the probe of STM or AFM, *x*–*y* platform, read–write head of storage, the operational hands of robot and so on.

3. Experiment and analysis

A grating with 0.1 μm resolution is used to test this novel stepper motor. It is fastened on the slider and faces the linear encoder, which records the displacements of slider and translates them into digital signals. A software is developed to process these digital signals. The period of the data transfer from the linear encoder to computer is 1 ms. The duration of high level ranges from 0.1 ms to 1000 ms and the duration of low level is about 1/5 times of that of the high level. The pulse amplitude varies between 150 V and 250 V.

Fig. 4 presents the displacement–time relation for the pulse amplitude of 250 V and the duration of high level of 1000 ms. As stated before, the actuator is driven two times during a period of the pulse, so there should be two types of steps in the graph, i.e. longer steps and shorter steps. The longer one should persist 1000 ms and the shorter one about 200 ms or so as can be seen in Fig. 4.

The shorter steps cannot be found and the heights of almost all steps are 0.1 μm when the amplitude of the high level is 150 V. However, the persisting time of the longer steps is several times of 1000 ms. It means that several pulses were applied to drive the slider within the time a step persisting. The displacement of single step is smaller than 0.1 μm. The displacements of several steps accumulate to 0.1 μm, which can be recorded by the linear encoder.

The actuator moves in stepping mode when lower frequency pulses are applied to drive it. The movement driven by each pulse is divided in time. In other words, the actuator is driven to move a distance by the high level. When the low level comes, the deformation of ceramics disappears and the actuator is driven by spring to reach a new position and then stops. The frequency of the movement is consistent with that of the pulse. The actuator can be driven to move only if the deformation stress of the piezoelectric ceramics adding the elasticity of spring conquers the friction between the slider and the guideway. Varying the pulse amplitude can only change the range of the actuator but not its stepping mode. However, as can be seen later, if the duration of the high level is small enough (<1 ms), the stepping mode will be destroyed.

Fig. 5 shows the displacement–time curve of the actuator when the duration of the high level is 100 ms, where longer steps and shorter steps can be clearly observed. Most of longer steps persist 100 ms and shorter ones persist 18 ms. While the pulse amplitude decreases to 150 V, the result of experiment is similar to what is observed when the duration of high level is 1000 ms.

In all experiments, the system noise can influence the results. As can be found in Fig. 4 and Fig. 5, the heights of most noise steps are 0.1 μm and their persistent time is 1 ms or several milliseconds. The resolution of the grating is 0.1 μm and the period of the data transferring from linear encoder to computer is 1 ms. Then the noise comes from the testing system. If the laser interferometer is used in the testing system, due to its higher resolution, the noise may be suppressed. However, it cannot be used as feedback facility in the high precision positioning closed loop system. With the decrease of the duration of the high level, the system noise influenced the results more seriously. Fig. 6 shows that, although the linearity of actuator is good and stepping character is obvious too as the duration of high level decreases to 10 ms, there are some oscillations in each step due to the existence of the noise. The longer

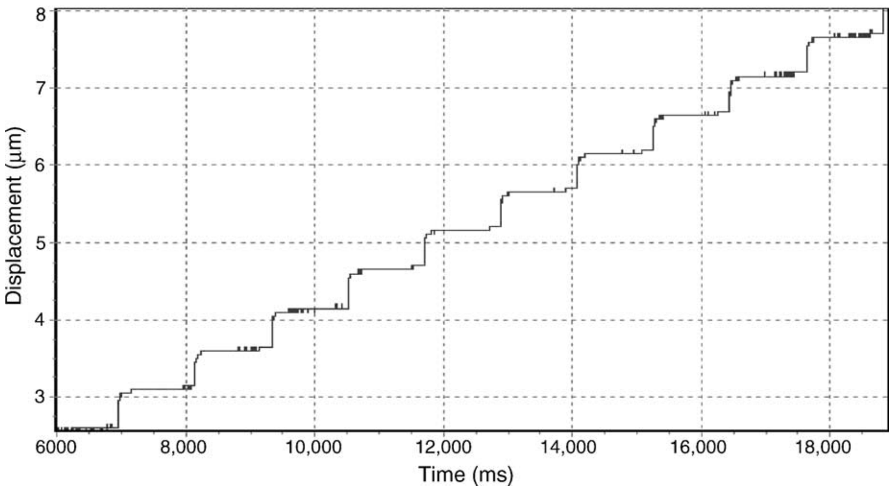

Fig. 4. The displacement–time curve when the duration of high level is 1000 ms and the pulse amplitude is 250 V.

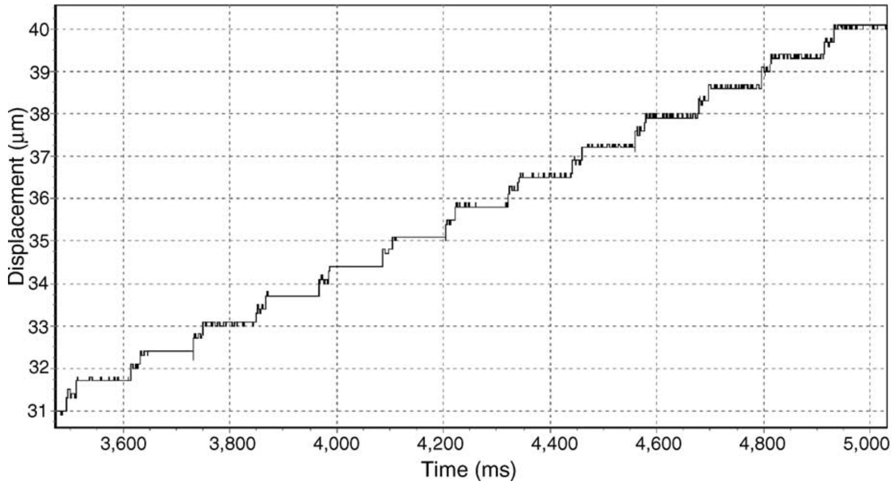

Fig. 5. The displacement–time curve when the duration of high level is 100 ms and the pulse amplitude is 250 V.

steps and the shorter steps cannot be distinguished clearly. The range of the actuator changes obviously when the amplitude of pulse change. The step heights are decided by the amplitude of the high level and step lengths are decided by the duration of the high level when lower frequencies pulse waveform was applied to drive the actuator.

With the further decrease of the duration of the high level, the stepping character is obvious too, but the influence of noise is getting more and more serious.

If the duration of high level is below 1 ms, most steps persist 1 ms and almost all heights of steps are 0.1 μm. The difference between the results of 1 ms and below 1 ms is that the heights in 1 ms case are higher than that of 0.1 μm. Fig. 7 presents the displacement–time curve as the duration of high level is 1 ms and pulse amplitude is 250 V. An obvious character of this curve is that there is only rise steps but not fall steps. The heights of the steps range from 0.3 μm to 1.1 μm. In principle, the longer step will persist 1 ms, the same as the persistent time of the noise, so the noise does not exhibit itself as oscillations but as the variations of the heights of the steps. In Figs. 4–6, the heights of the steps are almost invariable, but in Fig. 7, the heights of the steps are varied. Because the heights of the steps due to the displacement signal is bigger than those due to the noise, we can only observe the increase of the displacement with the time in the figure. Under 250 V pulse amplitude, In the case of 1 ms, the actuator achieves the highest speed and longest range. Besides, it still has a very good linearity. The shortcoming is the heights of the steps are variable, which is related to the friction and the system noise.

Ten million data points were collected when the amplitude of the pulse is 250 V and the duration of high level is 0.5 ms and the result is shown in Fig. 8. The heights of most steps are 0.1 μm and they persist for about 1 ms. The noise cannot be found directly in Fig. 8. However, the facts that not all heights of the steps are 0.1 μm and not all persistent time of the steps are 1 ms reflect the existence of the noise. If the actuator moves in stepping mode and considering that the period of the data transfer from the linear encoder to computer

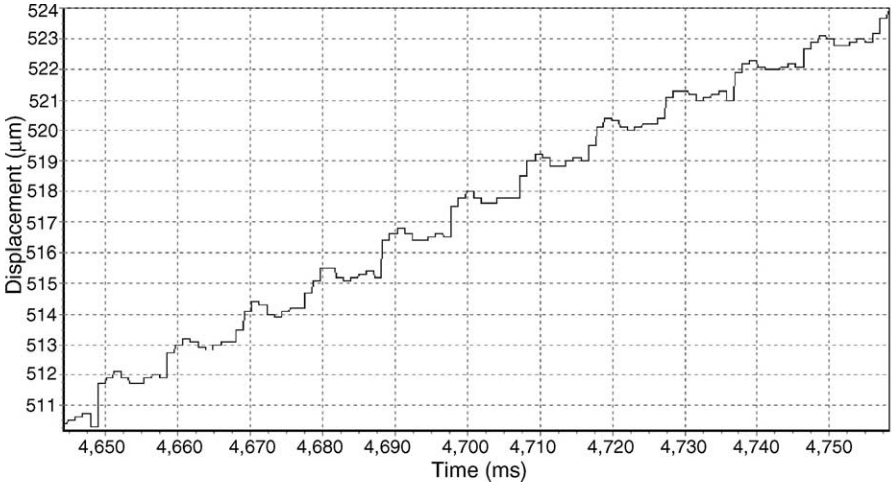

Fig. 6. The displacement–time curve as the duration of high level is 10 ms and the pulse amplitude is 250 V.

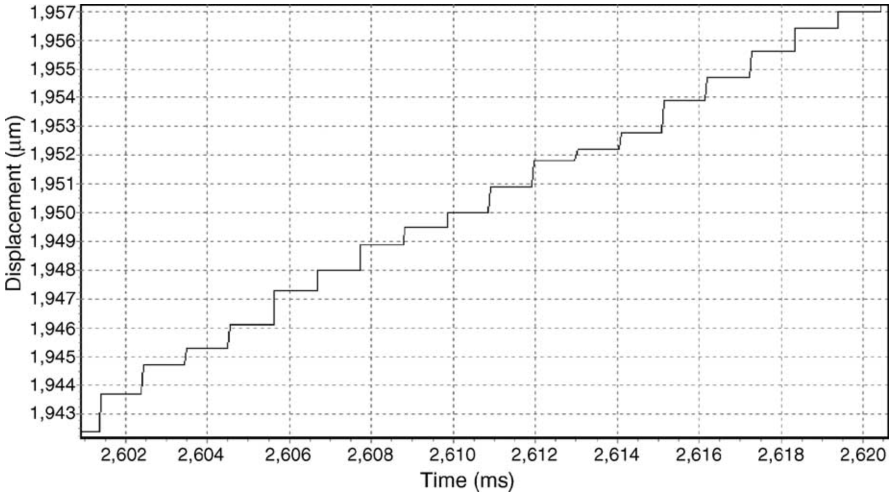

Fig. 7. The displacement–time curve as the duration of high level is 1 ms and the pulse amplitude is 250 V.

is 1 ms, the steps should persist 1 ms and their heights should be around 0.6–2.2 µm. However, such expected results cannot be observed in Fig. 8. Besides, because the deformation of ceramics is linear with the pulse amplitude, the heights of the steps should vary with the pulse amplitude. However, we have not observed such results when the pulse amplitude decreased from 250 V to 150 V. The reason is that the frequency of the pulse waveform is too high for the actuator to respond. In other words, before the actuator finishes the movement driven by a pulse, the next one comes. Some electrical energy is lost and cannot be transformed into kinetic energy, thus the stepping mode is destroyed. The steps observed in the figure come from the testing system whose resolution in time is 1 ms and in displacement 0.1 µm. When the duration of high level is changed to be 0.1 ms, 0.2 ms, 0.7 ms and 0.9 ms, the results are similar to what has been shown in Fig. 8. The range of the actuator changes with the frequency of the pulse. The higher the frequency of the pulse, the shorter the range of the actuator is. That is to say, for the higher frequency, much electrical energy of the pulse is lost.

According to the principle of the actuator, if the actuator moves in stepping mode when the duration of high level is 1 ms, the shorter steps should appear in the curve. However, because the persistent time of the shorter steps is about 0.2 ms, which is too small to be distinguished by the testing system, in fact, the shorter steps have merged with the longer steps.

Fig. 9 shows the relation between the velocity of the actuator and the frequency of the pulse. As can be seen in the figure, the actuator achieves the highest speed and the longest range when the duration of high level is 1 ms. In fact, in this case, the actuator moves in stepping mode. No electrical energy of the pulses is lost comparing to high frequency and there are more pulses to drive it than that of low frequency in the same time. The actuator can be controlled easily by changing the

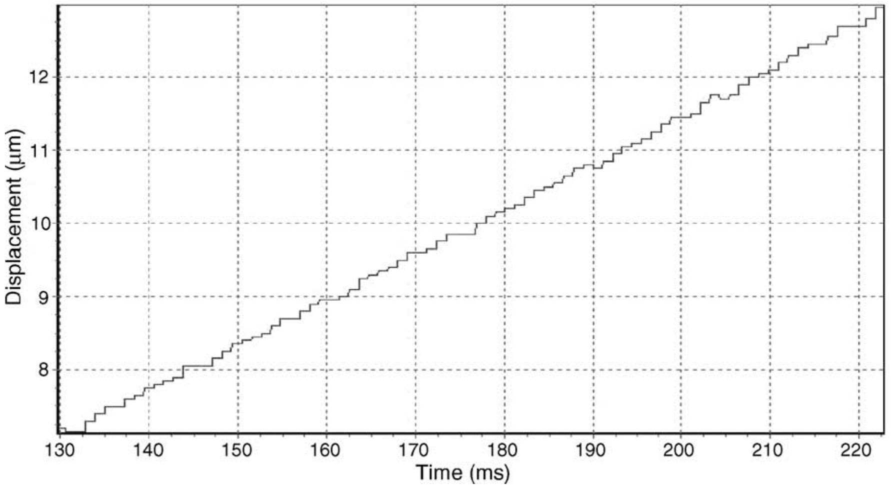

Fig. 8. The displacement–time curve when the duration of high level is 0.5 ms and the pulse amplitude is 250 V.

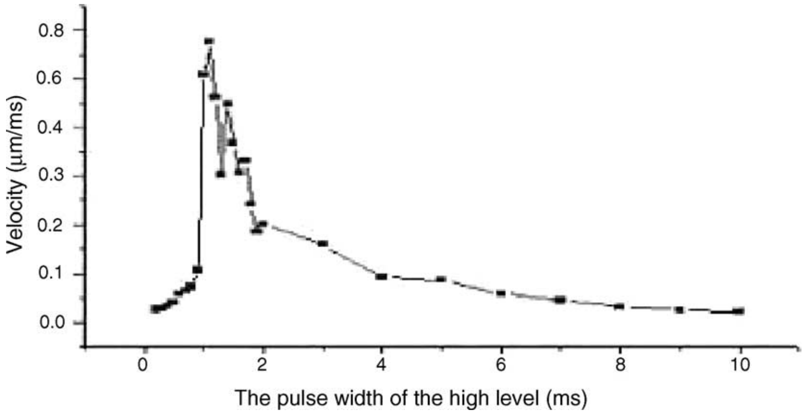

Fig. 9. Relation between the velocity of the actuator and the duration of the high level.

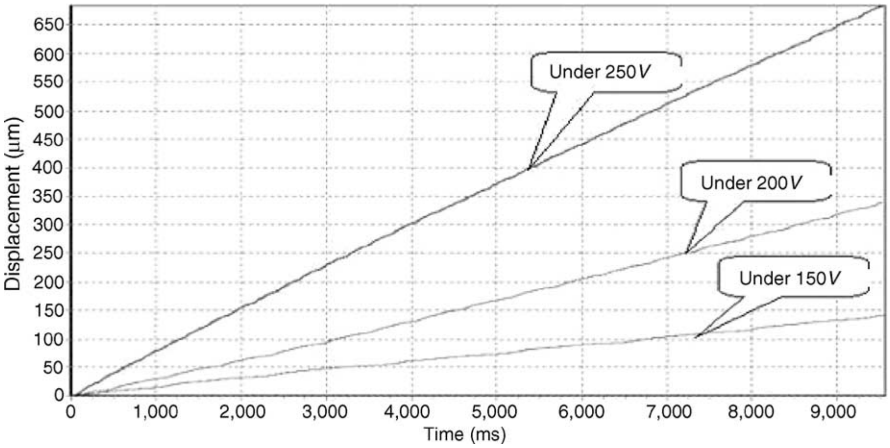

Fig. 10. The displacement of the actuator moving under the different amplitude, same frequency pulse waveform.

amplitude or changing the frequency of the pulse waveform. The amplitude and the frequency of the pulses used in the experiments can be varied successively. Then this kind of actuator can be used easily in high precision positioning closed loop system.

The relation between the range of the actuator and the pulse amplitude is shown in Fig. 10. The higher the pulse amplitude, the longer range of the actuator while the actuator moves in stepping mode. When the pulse amplitude decreases to 200 V, the range of the actuator is shorter than that when the amplitude is 250 V. The reason is that the deformation of the ceramics becomes slighter with the decrease of the pulse amplitude. The displacements driven by each pulse should be smaller and the energy saved in spring is smaller, which leads the elasticity of the spring to be smaller. Results of other experiments also accord to this idea if the amplitude of the high level ranges from 250 V to 150 V but the duration of the high level is still.

From the above experimental results, it is clear that the actuator moves in stepping mode when the duration of the high level is longer than 1 ms, but if the duration is shorter than 1 ms, the stepping mode will be destroyed.

4. Conclusion

This paper reports the fabrication of a novel type of linear stepper actuator with piezoelectric ceramics. The actuator has been tested under different frequencies and amplitudes of the pulse waveform. It has been found that the actuator moves in stepping mode under lower frequency pulse and the stepping mode is destroyed under higher frequency pulse. This actuator achieves the highest speed and the longest range when the duration of high level is 1 ms. The actuator can be controlled easily by changing the amplitude or the frequency of the pulse. Its resolution of single step can be 0.1 μm and its highest speed may be 0.6 mm/s. Its range may be several centimeters, its load may be 200 g and its configuration is simple. The shortcomings of the actuator are that it can only move in one direction and is not easy to miniaturize.

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Biographies

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