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Influence of Waveform Symmetry on Output Performance of Piezoelectric Inertia Actuator Controlled by Composite Method

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Abstract. The waveform symmetry has a great influence on the piezoelectric inertia actuator. In this paper, the waveform symmetry based on the composite method is explained and its influence on the output performance is discussed in relation to four aspects: frequency characteristics, voltage characteristics, load capacity, driving capacity. The designed prototype is fabricated and a series of experiments are carried on. Experiments show the waveform symmetry based on the composite method is widened effectively relative to the traditional driving method. The high-speed of the actuator is obtained under 60% and 40%.The large-load is achieved under 90% and 10%. When the saw-tooth driving waveform voltage is 30 V_{p-p} for 800 Hz and a sinusoidal friction regulation waveform voltage is 6 V_{p-p} for 39 kHz, the maximum velocities in the forward and reverse direction are 1.48 mm/s and 1.39 mm/s. Meanwhile, the maximum vertical loads of the actuator are 540 g and 510 g. The actuator driven by different symmetrical composite waveforms will make it ideal for miniature devices.

1. Introduction

Piezoelectric inertia actuator has been developed for several decades because of their compact structure, immunity from magnetic interference, theoretically unlimited movement, low production cost [1-4]. Given these advantages, the inertia actuator have become viable candidates for using in camera focusing mechanisms, cell phones, scanning probe microscopes, zoom lens systems, and blue-ray devices. The specifications of inertia actuators mainly contain velocity, load, and driving capacity. The tradeoff between the velocity and load should be considered depending on different applications. The driving capacity is generally expected to be high for fitting into the miniature devices [5-6].
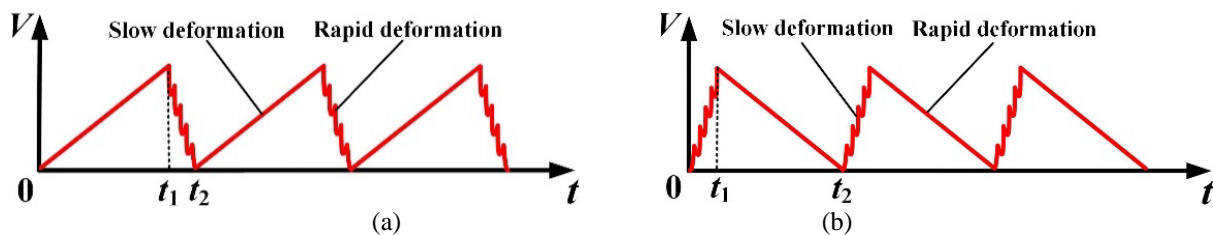
As one type of driving methods for piezoelectric inertia actuators, a traditional saw-tooth waveform is generally used as an exciting signal that includes slow and rapid deformation stages. However, the kinetic friction force in the rapid deformation stage frequently results in backward motion [7-10]. The composite method can restrained the backward motion effectively. It need to be pointed out that the waveform symmetry of the composite method has a great influence on output performance of inertia actuator. Thus, the goal of this work is to provide a comprehensive research on the symmetry of the proposed method. Previously, researchers have done some work related to waveform symmetry on performance aspect of actuator. Yuting Ma *et al.* researched the performance of the resonant-type inertial impact motor driven by the different symmetric rectangular pulse methodology. With the optimized waveform symmetry, both the velocity and load could be enhanced. Thus, there is an

optimal symmetry value to generate the high-speed and large-load capacity, which could be used in practical applications [11]. Chia-Feng Yang *et al.* studied the stepping motion of the piezoelectric device based on various symmetric triangular waveforms. This work proposed an impulse model to describe its motion behavior and indicates that not all inputs of waveform symmetry can work well. A proper symmetry can make piezoelectric actuator more suitable for use in high precision position and control [12]. Yuxin Peng *et al.* presented that the waveform symmetry has a distinct effect on the driving characteristics of linear actuator, especially for the precision positioning of the dual objects. The results indicate that the proposed actuator excited by different waveform symmetry can be better applied to different positioning applications [13]. Although there have been some studies on the waveform symmetry, it is still necessary to research the different symmetric composite method on the performance of inertia actuator. This paper will further provide an important guiding principle for the proposed method in practical applications.

2. Waveform symmetry

Figure 1 illustrates waveform symmetry distribution diagram of composite method in the forward and reverse direction. This method is realized by a composite waveform that includes a saw-tooth driving waveform and a sinusoidal friction regulation waveform, and the sinusoidal friction regulation waveform is applied to the rapid deformation stage of the saw-tooth driving waveform.

Figure 1. Waveform symmetry distribution of composite method. (a) is the waveform symmetry distribution in forward direction; (b) is the waveform symmetry distribution in reverse direction.
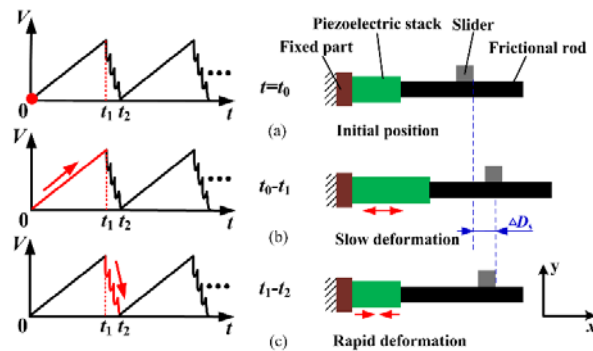
To describe the performance of actuator by different waveform symmetry, the waveform symmetry S based on composite method is defined as following:

$$S = \frac{t_1}{t_2} \times 100\% \qquad (1)$$

where S is waveform symmetry of composite method; $0 \sim t_1$ is the time of driving voltage going up; $0 \sim t_2$ is driving cycle. The waveform symmetry is changed by adjusting time ratio of t_1 and t_2. Figure 1(a) and (b) show that the hybrid waveform in the forward and reverse direction.
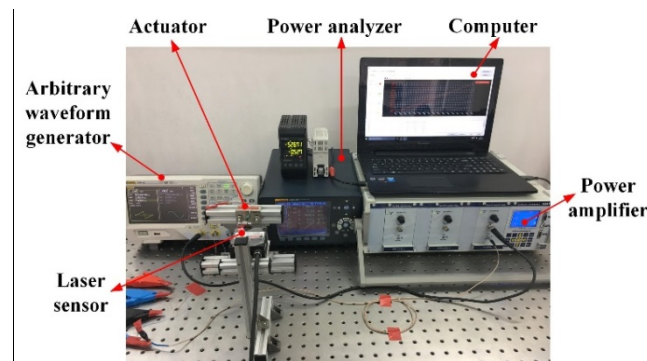
3. Driving principle

For an inertia actuator, an asymmetric motion is essential to provide stick and slip motions with its friction partners. The composite waveform seen in Figure. 1 is selected to drive the inertia actuator. According to Figure 2, the operation process of actuator in a driving cycle is explained in detail. When the applied voltage increases at relatively low speed, the slider moves with the stator along to the x direction; when the voltage decrease quickly, the stator goes back to initial position and the slider slips against the stator in the x direction due to inertial force. The backward motion is generated due to kinetic friction force between the slider and stator. Compared with traditional sawtooth waveform, the composite waveform can excite the stator to generate a micro vibration in rapid deformation stage. By this micro vibration, the backward motion of the actuator is obviously restrained. The large effective step displacement ΔDS in one direction is obtained, and a continuous stepping motion is achieved by cyclic composite waveform. By changing the waveform symmetry, the moving direction of the slider can be reversed.

Figure 2. Driving principle of inertia actuator under the composite waveform. (a) is the initial position;(b) is the slow deformation stage;(c) is the rapid deformation stage.

4. Experimental system

Figure 3 is the established tested system. The main parts of the system includes a computer, a power analyzer (NORMA4000, Fluke Co. Ltd, America), a laser sensor (LK-H020, Keyence Co. Ltd, Japan), an arbitrary waveform generator (DG4162, Beijing RIGOL Technology Co. Ltd, China), a power amplifier (XE500-C, Harbin Core Tomorrow Science & Technology Co. Ltd, China), and a actuator. When the tested system works, the arbitrary waveform generator controlled by the computer is used to provide a composite waveform. The arbitrary waveform generator voltage range is from -10 V to +10 V. The voltage is amplified by power amplifier, and the enlarged voltage signal is used to drive the prototype. The prototype is excited to generate a continuous output motion. A laser sensor with the resolution of 20 nm is used to measure its motion behavior, and the test data are gathered by its built-in software via computer. Meanwhile, the power analyzer is used to measure its input power.
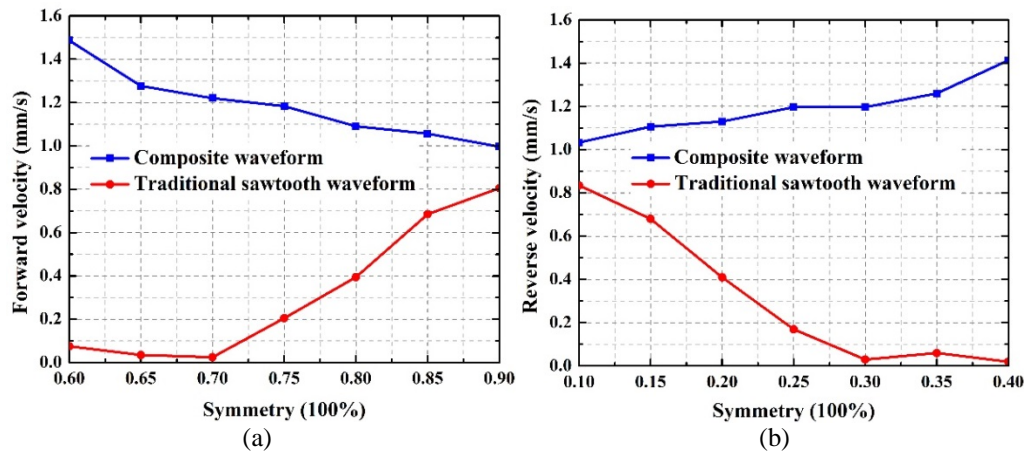

Figure 3. The established tested system for inertia actuator.

5. Results and discussion
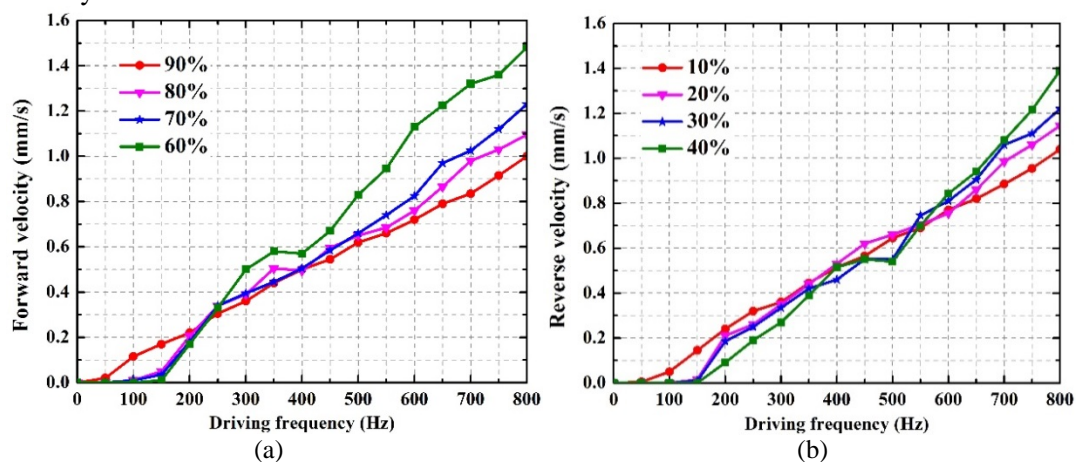
5.1. Symmetry characteristics

The parameters of the traditional sawtooth waveform are the same as the saw-tooth driving waveform. For the traditional driving method, the designed actuator cannot work normally in between 30%~50% and 50%~70% in both directions because no obvious saw-tooth type displacement is output. The large velocity can be obtained when the waveform symmetries are near 90% and 10%. The waveform symmetry in between 75%~90% and 10%~25% can be used in practical applications, as shown in figure 4 (a). For the composite method, the high velocity can be easily obtained relative to traditional sawtooth waveform. When the waveform symmetry is 50%, the velocities of the actuator can reach 1.72 mm/s and 1.74 mm/s in forward and reverse direction, as shown in figure 4 (b). The waveform diagram of 50% in forward and reverse direction is different. The larger operation range of the composite method is realized. Thus, the waveform symmetry is widened effectively relative to traditional driving method.

Figure 4. Velocity of the actuator versus to waveform symmetry. (a) is the forward velocity with the hybrid and traditional driving waveform; (b) is the reverse velocity with the hybrid and traditional driving waveform.

5.2. Frequency characteristics

Figure 5 shows the curve of the output velocity versus the driving frequency with different waveform symmetry at the load of 30 g when the saw-tooth driving waveform voltage is 30 $V_{p\text{-}p}$, and the sinusoidal friction regulation waveform voltage and frequency are 6 $V_{p\text{-}p}$ and 39 kHz. The velocity of the actuator has an increasing trend with the frequency from 0 Hz to 800 Hz. The results indicate that the velocity of the actuator under different waveform symmetry has a slight change in between 300 Hz and 500 Hz in both directions .Before the frequency of 300 Hz, the high velocity is realized under 90% and 10%, and the actuator starts to work at 50 Hz. The larger frequency operation range can be achieved due to the small driving frequency, which is more suitable for velocity control of fine motion. After the frequency of 300 Hz, the actuator under the symmetries of 60% and 40% can achieve high velocity, and the output velocities are 1.47 mm/s and 1.46 mm/s at 800 Hz in two directions. The relationship between the frequency and velocity is not linear. This may be caused by preloading gap and assembly errors.
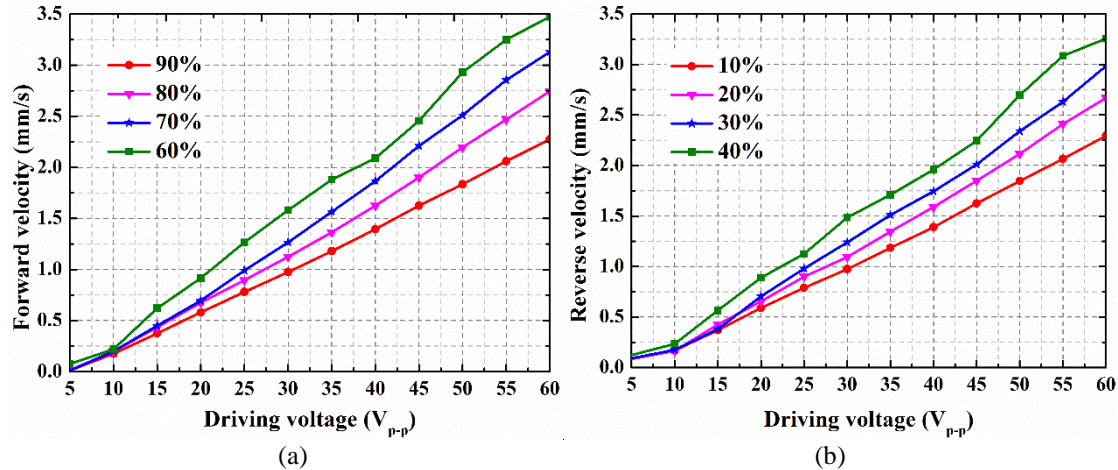

Figure 5. Velocity versus to frequency at the vertical load of 30 g. (a) is the forward velocity with symmetries of 60%~90%; (b) is the reverse velocity with symmetries of 10%~40%.

5.3. Voltage characteristics

Figure 6 shows the relationship between velocity and driving voltage in both directions at 30 g when the saw-tooth driving waveform frequency is 800 Hz, and the sinusoidal friction regulation waveform voltage is 6 $V_{p\text{-}p}$ for 39 kHz. The velocity linearly increases with driving voltage from 5 $V_{p\text{-}p}$ to 60 $V_{p\text{-}p}$. The results indicate that there is no significant change in the performance of the actuator under different waveform symmetries before the voltage of 20 $V_{p\text{-}p}$, and the minimum driving voltage is 5
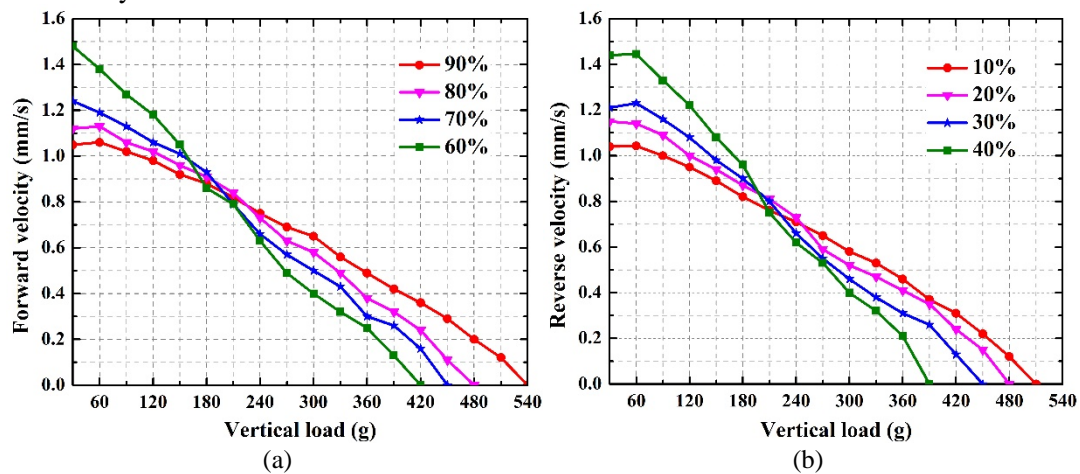
V_{p-p}. Thus, the actuator is particularly applied to high precision position and control, and its work is not easy to generate the heat. After the voltage of 20 V_{p-p}, the waveform symmetry has an obvious influence on the actuator. When the voltage is 60 V_{p-p} the actuator can achieve the velocities of 3.48 mm/s and 3.26 mm/s under 60% and 40%. Meanwhile, under 90% and 10% the velocities of the 2.27 mm/s and 2.29 mm/s can be obtained. The actuator is suitable for zoom lens systems and camera lens modules that require high velocity.

Figure 6. Velocity versus to voltage at a vertical load of 30 g. (a) is the forward velocity with the symmetries of 60%~90%; (b) is the reverse velocity with the symmetries of 10%~40%.

5.4. Load capacity

The standard weight is used to investigate load characteristics along negative direction. The relationship between vertical load and velocity is illustrated in Figure. 7. The initial mass of slider is 30 g without load. The various loads were loaded on the slider during the experiments. It is seen that the velocity decreases when the vertical load becomes large. The forward maximum vertical loads are 540 g when the symmetries are 90%. The reverse maximum vertical loads are 510 g when the symmetries are 10%. Thus, the actuator excited by the hybrid driving waveform could be suitable for the information technology devices that require large-load operation. In addition, the velocity of the actuator are nearly equivalent in both directions when the vertical load is 210 g, the large velocity can be obtained under the symmetries of 90% and 10%. Thus, a larger stiffness of the actuator is obtained relative to the symmetries of 90% and 10%.

Figure 7. Velocity of the actuator versus to the vertical load. (a) is the forward velocity with the symmetries of 60%~90%;(b) is the reverse velocity with the symmetries of 10%~40%.

Taking into account the potential application value of the actuator, the load capacity excited by different symmetrical hybrid actuation waveform is further quantified. An important of the mass ratio λ is defined by as follows:

$$\lambda = \frac{M_m}{M_s} \tag{2}$$

where λ is the mass ratio, M_m is the maximum vertical load, M_s is the mass of stator, and its mass is 4 g.

The maximum vertical load and mass ratio are listed in Table 1.

Table 1. The maximum vertical load and mass ratio in forward direction and reverse direction.

Symmetry (100%)	Forward direction				Forward direction			
	90%	80%	70%	60%	40%	30%	20%	10%
M_m (g)	540	480	450	420	390	450	480	510
M_s (g)	4	4	4	4	4	4	4	4
λ	135:1	120:1	113:1	105:1	98:1	113:1	120:1	128:1

According to Table I, the forward mass ratio can reach 135:1 under waveform symmetries of 90%. The reverse mass ratio is 128:1 under symmetries of 10%. Thus, the actuator under 90% and 10% can easily achieve the large-load operation.

6. Conclusions

In this paper, the waveform symmetry based on the composite method is researched. The waveform symmetry is explained, and the driving principle of composite waveform is analyzed. A prototype of the inertia actuator is fabricated and its output characteristics are tested. The tested results indicate that the maximum velocities are 1.48 mm/s and 1.39 mm/s under 60% and 40% when the saw-tooth driving waveform voltage of 30 V_{p-p} for 800 Hz and sinusoidal friction regulation waveform voltage of 6 V_{p-p} for 39 kHz. The inertia actuator can be used in practical application that required high-speed operation. The maximum vertical loads of the actuator are 540 g and 510 g under 90% and 10%. Correspondingly, the maximum mass ratio is 135:1 and 128:1. Thus, the actuator can achieve the large-load operation. In addition, the waveform symmetry of the composite method is widened relative to the traditional sawtooth waveform. This paper will provide an important guiding principle for the method in practical applications. Because of the simple structure and low cost of both mechanical and electrical parts, the proposed actuator is a promising information technology devices for use in camera, manipulator systems and blue-ray equipment.

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