Turned off Characteristics of Linear Ultrasonic Motor

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Abstract: The high controllability and high resolution control of linear ultrasonic motors depend on effective control of driving signals. For a good control characteristic, step control which the driver output turned off and on was used. Therefore, a novel dual PWM topology structure ultrasonic motor driver was designed and analyzed. According to the characteristics of the circuits, two kinds of hardware turned off methods named methods A and B were discussed. The differences of the voltage applied on motor by different methods were figured out. Finally, a series of experiments were carried out in the clean room to study the influence of step characteristic by different turn off methods. The experimental results show that the steplength was 230 nm by method A and 125 nm by method B, while cycles of driving signals were 6. The method B has a smaller steplength when cycles are 6. The average steplength varies in non-linear while driving cycles changing. The steplength varies approximately in linear while voltage amplitude changing. Therefore, method B is better to implement step control, because it gets a better control in positioning system.

Key words: linear ultrasonic motor; turned off characteristics; step control; steplength

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0 Introduction

Linear ultrasonic motors[1-4], as a typical application of piezoelectric technology, have many attractive features such as directly produce linear motion, simple structure, large stroke, self-locking, high positioning accuracy, no electromagnetic interference and good environment compatibility. And linear ultrasonic motors have become a powerful supplement to the traditional electromagnetic motor in the field of high precision. The high precision positioning tables driven by linear ultrasonic motors have been commercialized by some foreign companies and well used in scientific research, industrial control, biomedical engineering, aerospace and other fields[5-7].

According to the operating mechanism of linear ultrasonic motors, the speed of motor can be controlled by the driving voltage, frequency and phase difference of the two-phase power sources[8-10]. Noting that the butterfly-shaped linear ultrasonic motor[11-13] is operated under symmetric mode and anti-symmetric mode, the frequency responses are inconsistent of the two operating modals due to structure parameters. The method by adjusting driving frequency is thus relatively unsuitable for speed control of motor. Since changing driving voltage method supports better linearity than other methods, the linear ultrasonic motor is often controlled by driving voltage method. However, it poses a control challenge at low command voltage, an effect known as dead zone, due to factors such as the varying quality of contact interface between the stator and the mover, the performance of piezoelectric ceramics, and so on. The existence of dead zone leads to a bad control performance of motor. Therefore, the step control[14-15], in which the

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output of driver is hardware turned off and on, is used to drive the motor in discrete steps. Thus, the precision control of driver output, especially the number of waves applied on motors, is important to get the better control characteristics and the higher positioning resolution.

A novel kind of dual PWM topology ultrasonic motor driver was designed and analyzed in this paper. According to the driver circuits, two kinds of hardware turned off methods were provided. The influences of hardware turned off response characteristics of motor were measured in the clean room and discussed according to the experimental results. Based on an effective hardware turned off control mechanism, the high controllability and high resolution of linear ultrasonic motor were achieved.

1 Principles

The step control of linear ultrasonic motor is used by turning the driving signal off and on in a carefully designed sequence. The steplength is decided by the width of driving signals. The fluctuations in velocity will affect the uniform of each step, especially when the steplength is small. As shown in Fig. 1, the steplength S_{tp} is defined by the displacement of n cycles of driving signals applied on motor, and the phase difference of phase A and phase B is 90°.

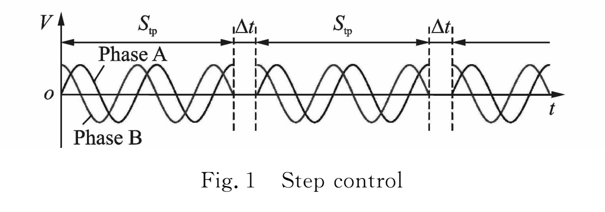

Fig. 1 Step control

The process of motor single-step response is described by motor transient characteristics[16], as shown in Fig. 2. During the time 0—t_1, the velocity of motor accelerated to v_1. At the time of t_1, the power was shutdown, and the velocity of motor was gradually decelerating. At the time of t_2, the motor stopped completely. Therefore, the steplength equals to the displacement during the time 0—t_2.

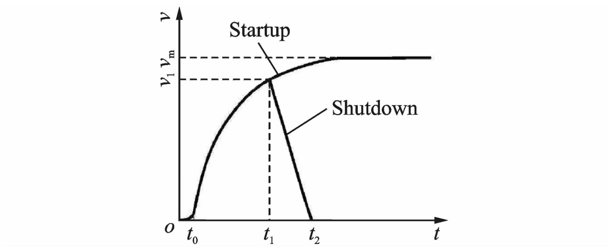

Fig. 2 Motor transient characteristics

During the time of 0—t_1, the displacement of motor S_{tp1} can be written as

$$S_{tp1} = \int_0^{t_1} v\mathrm{d}t = \int_0^{t_1} v_{\max}(1 - \mathrm{e}^{-t/\tau_1})\mathrm{d}t =$$

$$v_{\max}t_1 + v_{\max}\tau_1(\mathrm{e}^{-t/\tau_1} - 1) \tag{1}$$

where $\tau_1 = m/c_\tau$, m is the mass of the platform, c_τ the damping coefficient of motion, and $v_{\max}$ the maximum velocity of motion.

During the time of t_1—t_2, the displacement of motor can be expressed as

$$S_{tp2} = v_{\max}(1 - \mathrm{e}^{-t_1/\tau_1})(t_2 - t_1)/2 \tag{2}$$

Thus, the displacement of motor during the time of 0—t_2 can be described as follows

$$S_{tp} = S_{tp1} + S_{tp2} \tag{3}$$

Therefore, the number of driving signals can be expressed as

$$n = t_2 f \tag{4}$$

where f is the driving frequency applied on motor.

Actually, during the time of 0—t_0, the displacement of motor is 0 because of the dead zone of motor, and thus the minimum number of driving signals is greater than $t_0 f$.

2 Methods

Frequently, driving ultrasonic motor needs to apply power with ultrasonic frequency, high voltage and certain phase difference. A motor driver is important for application of ultrasonic motors. The quality of the driver affects motor′s output performance and its applications. According to topological structures, the power amplifier circuit made of MOSFET has three types, such as push-pull converter, full bridge converter and half bridge converter. In order to achieve decouple control of driving signal and load with adjustable multi-parameter, a novel dual PWM topology ultrasonic motor driver was developed with linear characteristics of output driving signals and the independent control of driving voltage and frequency.

As shown in Fig. 3, single output of dual PWM topology structure ultrasonic motor driver consists of three parts. The first part is a half bridge converter, and the MOSFETs Q_1 and Q_2 conduct alternately in order to convert power VDD to square waveform with certain duty ratio. The second part is a push-pull converter, and the MOSFETs Q_3 and Q_4 conduct alternately through the middle point of the primary side of the transformer. The unipolar square waves alternately applied to the gate are converted to bipolar square waves by this circuit. Due to very low conducting resistance and leak current, the loss of MOSFETs is very small in the period from ON to OFF. The last part is a coupled resonance circuit to filter the unnecessary harmonic waves for achieving a basic wave, and avoid exciting the non-operation modes of a stator. The capacitor C is in parallel with the stator or the secondary side of the transformer[17-18]. The half bridge converter and push-pull converter are connected with inductor L_0, to implement constant current and high impendence. The frequency applied on G_1 and G_2 is always twice of working frequency, and the frequency applied on G_3 and G_4 equals to working frequency. It needs to ensure that the voltage applied on G_1 holds low level when level of G_3 changing. Thus, the output voltage of the driver is linearly related to the duty ratio of signal applied on G_1 and G_2.

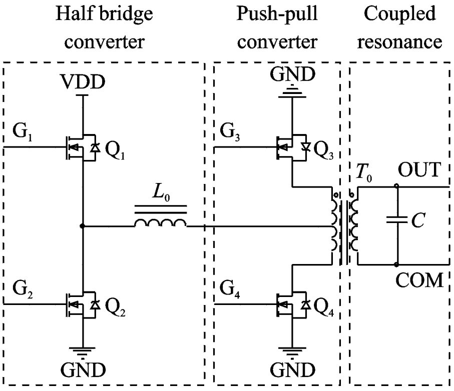

Fig. 3 Single output of dual PWM topology structure

According to the topology structure mentioned above, there are two kinds of methods to turn off driving signals during step control. As shown in Table 1, the differences between method A and method B are the state of MOSFETs named Q_3 and Q_4. The method A turns on the MOSFET Q_2 and turns off the MOSFETs Q_1, Q_3 and Q_4, when driver hardware turned off. In this case, the residual energy of the transformer T_0 is drained through the inductor L_0 and the MOSFET Q_2. The method B turns off the MOSFET Q_1 and turns on the MOSFETs Q_2, Q_3 and Q_4, when driver hardware turned off. Therefore, the residual energy of the transformer T_0 will drain through the MOSFETs Q_3 and Q_4 directly as fast as possible.

Table 1 State of MOSFETs when hardware turned off

MOSFET	Method A	Method B
Q_1	OFF	OFF
Q_2	ON	ON
Q_3	OFF	ON
Q_4	OFF	ON

Fig. 4 and Fig. 5 show the voltage applied on motor using different kinds of hardware turned off methods. The solid curve with red color shows the voltage applied on motor phase A, and the dotted curve with blue color indicates trigger signals to capture the moment while turning off the driver. At the falling edge of the trigger signal, the driver turned off. The result shows that the amplitude of driving signals applied on phase A was gradually attenuation to zero with method A. But the amplitude was dropped to zero immediately with method B in the same case. It is clear that driving signals attenuation faster using method B than method A. Therefore, method B is used to drive motors in order to achieve precision driving signals and obtain better control characteristics.

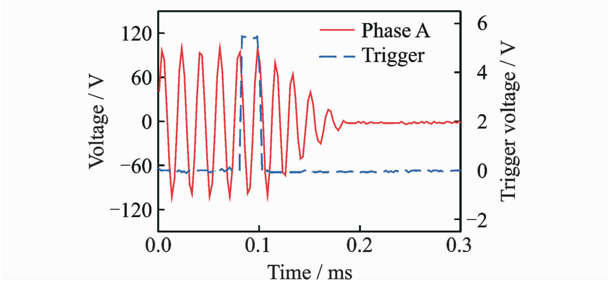

Fig. 4 Hardware turned off response of method A

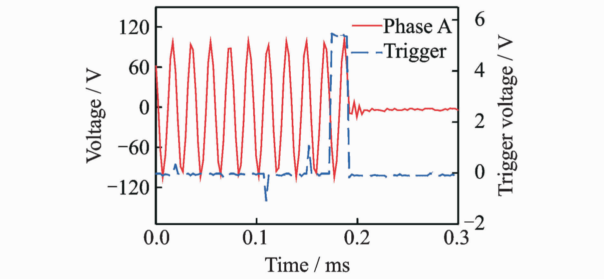

Fig. 5 Hardware turned off response of method B

3 Results and Discussion

A series of experiments were carried out in clean room with grade of 10^5 and vibration isolation has been effectively done. A laser interferometer (Renishaw XL-80) with linear measurement accuracy of $\pm 0.5 \times 10^{-6}$ is used to investigate step characteristics of positioning table driven by butterfly-shaped linear ultrasonic motor. The experiment setup is consist of laser interferometer, interference mirror, reflective mirror and positioning table, as shown in Fig. 6. The experimental temperature is 25 ℃, relative humidity is 60%, and the atmospheric pressure is 101.5 kPa.

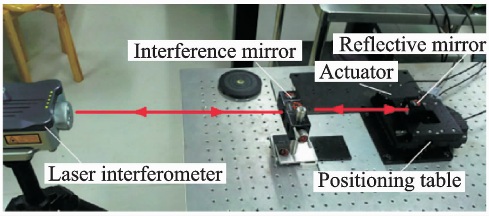

Fig. 6 Experimental setup

Figs. 7, 8 show the steplength by methods A and B under an open-loop condition, respectively. During the experiments, the driving frequency was 52.6 kHz, the driving voltage applied on motor was 120 V (peak to peak voltage), and the phase difference was 90°. When the cycles of driving signals generated by the driver were 6, and the driving period was 100 ms. According to the experimental results, the steplength of motor was uniformly distributed, the average steplength was 230 nm while using method A, and the average steplength was 125 nm while using method B.

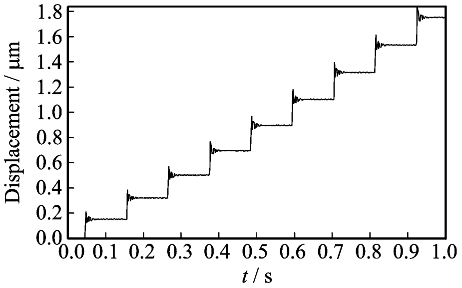

Fig. 7 Steplength by method A with 6 driving cycles

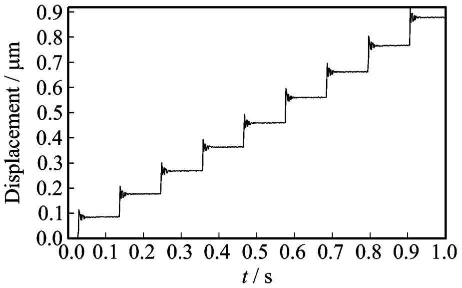

Fig. 8 Steplength by method B with 6 driving cycles

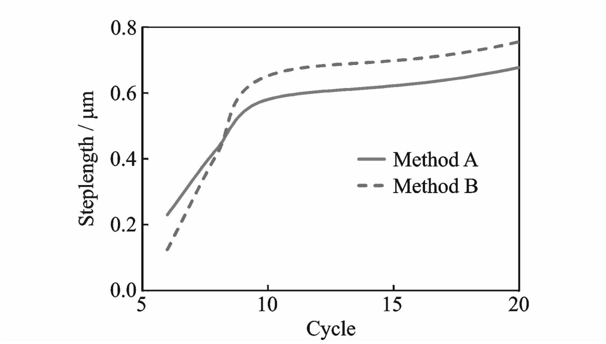

Fig. 9 Steplength with different driving cycles

As shown in Fig. 9, the steplength with different driving cycles by methods A and B. The driving frequency was 52.6 kHz, the driving voltage was 120 V and the phase difference was 90°. It can be seen from Fig. 9 that the steplength of motor was increased with driving cycles, however, it had strong nonlinearity. The steplength was smaller by method B while there were a few driving signals due to rapidly signal attenuation. As driving cycles increased, the influence of signal attenuation was decreased, and a larger steplength was obtained by method B.

Fig. 10 shows the steplength with different driving voltages. The driving frequency was 52.6 kHz, the phase difference was 90° and the cycles of driving signals were 6. The steplength of motor was increased with driving voltage, and the steplength varied approximately in linear by method A or B. It can be easily figured out that method B had a better linearity and a smaller steplength.

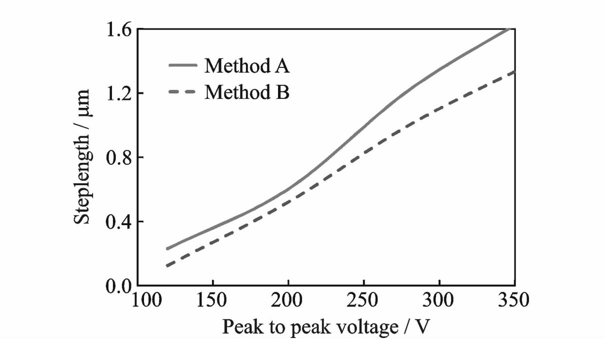

Fig. 10 Steplength with different driving voltages

In order to achieve high resolution by step control, the driving cycles of motor should be as few as possible. The steplength of method B is smaller at a few of driving cycles. And the steplength of method B is also smaller as driving voltage increasing. Considering there is a linear relationship between steplength and driving voltage, method B is better to achieve high precision step control than method A due to better linearity and smaller steplength.

4 Conclusions

A new type ultrasonic motor driver for linear ultrasonic motor is presented. To achieve better step control performance, two types of hardware turned off methods are discussed. Furthermore, a series of experiments were carried out in the clean room to measure step characteristics by different turned off methods. According to the experiment results, method B has a smaller steplength while driving cycles are 6, and the average steplength is about 125 nm. The steplength measured by method B varied approximately in linear while voltage applied on motor increasing. Thus, method B is a better plan to implement step control, in order to obtain better control performance in high precision positioning table system.

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