Traveling Wave Type Ultrasonic Linear Motor Using Twin Bending Bars

Shuichi KONDOa, Hiroshi YAMAURAa, Daisuke KOYAMAa, Kentaro NAKAMURAa*

a Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259-R2-26 Nagatsutacho, Midori-ku, Yokohama, 226-8503 Japan

Abstract

Ultrasonic linear motors with a small body are highly demanded since efficiency does not decrease very much with downsizing. In this study, we aim at realizing ultrasonic linear motor with the diameter less than 10 mm as an alternative to small air cylinder actuators. We propose a new stator structure using two PZT elements between two parallel bending bars. The PZT elements are bonded at the position of several mm from the bar end. In this structure, both bar ends vibrate resonantly in a bending mode, and high vibration displacement amplitude can be obtained along the bars. The length between the PZT element and the bar end determines the optimum driving frequency. The slider simply consists of three metal plates, which sandwich the bending bars, and the preload can be controlled by springs. The conditions in which the traveling wave can be generated along the bars were investigated. When the bars vibrate in a symmetric mode and traveling waves are generated, the slider moves in the direction opposite to traveling wave. Traveling wave could be generated by controlling the driving phase difference between the two PZT elements. It was found that the phase differences depend on the distance between the two PZT elements. We experimentally achieved the stroke of 10 mm and the thrust of 78 mN at 23 kHz.

Keywords: Ultrasonic motor; linear actuator; small body; traveling wave

1. Introduction

Recently, linear actuators are demanded to downsize for a robot in plants. Mainly air cylinders are used as linear actuator while they are large-scale because they require air pipes for the compressed air. So it is difficult to downsize air cylinders. Electromagnetic linear motors replace a part of air cylinders, but the efficiencies dramatically decrease with downsizing less than 20 mm in diameter. In this study, we aim at the realization of the small ultrasonic linear motor with the diameter of 10 mm. The ultrasonic motors have a good advantages such as high torque and high-speed reply. It is reported that the ultrasonic rotative motor of 70 mm in diameter obtained the maximum torque of 2 Nm[1], and the ultrasonic linear motor using a longitudinal and bending hybrid transducer of 40 mm in diameter obtained the maximum thrust of 92 N[2]. However, these ultrasonic motors use the transducers using own resonant length which is equal to several dozen mm, such as bolt-clamped Langevin PZT transducer.
There is a difficulty in downsizing on the ultrasonic motors. The driving type of the ultrasonic linear motor is divided into the standing wave type and the traveling wave type. At the former type, we can obtain a large thrust although by using loops of the resonance, a problem of the abrasion partly occurs on the contact point on the stator and slider. At the latter type, as loops moves by a traveling wave along the bar, the abrasion occurs not partly. In this study, we select the traveling wave type for the ultrasonic linear motor with downsizing. The target performance of the thrust, the stroke, and the velocity are 1 N, 10 mm, and 200 mm/s respectively.

2. The structure of the bending bars and the transducers

We propose the new stator structure of the traveling wave type ultrasonic linear motor shown in Fig.1. It consists of two small PZT elements (3×2×5 mm³) between two parallel bending bars of stainless steel (cross-section of 4×2 mm²), and the slider between the two PZT elements. We employed the multilayered PZT that the large vibration displacement amplitude can be obtained with small input voltage. These PZT elements are polarized in the vertical direction and vibrate to the vertical direction with VAC on the top and bottom. The stainless steel bars vibrate in a bending mode at optimal frequencies. If the traveling wave is generated along the bars between the two PZT elements, the surface of the bars behaves an elliptical motion. The slider can move to one-way direction through the frictional force, with the preload to the bending bars.

3. Determining the distance of the bar end

The two PZT elements are bonded at the position of several mm from the bar end, which is one of the important points of the proposed structure. We measured the vibration distribution with the experimental setup shown in Fig.2. The PZT element was bonded to only one end of the bars, and the other end was inserted into sand so as to absorb the bending traveling wave. When the length of the bar end $d$ is equal to 0 and 3 mm, the experimental result of the vibration distribution is shown in Fig.3(a) and Fig.3(b) respectively. Comparing the result of these, we can obtain the higher vibration displacement amplitude when both ends of bars vibrate resonantly. The vibration of the bar ends help the vibration displacement amplitude of the traveling wave obtain higher.

The resonance frequency of the bar end changes by the position of the PZT elements. The length of the bar end $d$ was changed in order to generate the fundamental mode on the bar ends and obtain the higher vibration displacement amplitude. In addition, the resonance frequency should be more than 20 kHz to avoid the generation of the noise. Using the experimental setup shown in Fig.2, we investigated the relationship between the resonance
frequency and the length of the bar end $d$. The wavelength of the traveling wave was also measured. The resonance frequency was confirmed by measuring vibration displacement amplitude at the top of the bar end with the LDV, and the wavelength was measured by scanning the vibration distribution along the length direction of the bar. The experimental result was shown in Fig.4. The length of the bar end $d$ should be longer to obtain the larger vibration displacement amplitude at the lower driving frequency. And the higher vibration displacement amplitude may be obtained in the 1st resonance mode than in the 2nd resonance mode. Since the resonance frequency should be more than 20 kHz, the length $d$ was determined to be 5 mm. The resonance frequency and the wavelength were 23 kHz and 28 mm respectively.

Fig.3 Comparison between the vibration distribution without bar end and with bar end.

Fig.4 The resonance frequency vs. the length of the bar end $d$.

4. Determining the distance between the two PZTs

We must consider the driving conditions in which the traveling wave can be generated along the bars to determine the distance between the two PZT elements. It is known that the traveling wave can be generated by two-phase drive[3]. Now consider the two PZT elements (A and B) are $L$ away, and they vibrate with the amplitude $U_0$ and the angular frequency $\omega = 2\pi f$, the spatial phase difference $\phi = 2\pi L/\lambda$, and the temporal phase difference $\theta$. The two waves are expressed as function of the position $x$ and the time $t$. 

\[ y(x, t) = U_0 \cos(\omega t - kx - \phi) + U_0 \cos(\omega t + kx - \phi) \]

\[ = 2U_0 \cos(\phi) \cos(\omega t - kx) \]

\[ = 2U_0 \cos(\phi) \cos(\omega t - \frac{2\pi x}{\lambda}) \]

\[ = 2U_0 \cos(\phi) \cos(\omega t) \cos(\frac{2\pi x}{L}) \]

\[ = 2U_0 \cos(\phi) \cos(\omega t) \cos(\frac{2\pi x}{L}) \]

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When we consider the superposition of those two waves, the vibration amplitude $u(x,t)$ is expressed as

$$U(x,t) = U_0 \cos \left( \phi + \theta \right) \cos \left( kx + \omega t + \frac{1}{2} \phi + \theta \right) + U_0 \cos \left( \phi - \theta \right) \cos \left( kx + \omega t + \frac{1}{2} \phi - \theta \right)$$

At the right side of this equation, the first term corresponds to the traveling wave to the positive direction, and the second term corresponds to the traveling wave to the negative direction. So $\theta \pm \phi = (2n + 1)\pi$ is the condition in which the traveling wave generates along the bar. This means that the direction of the traveling wave turns over by condition of $\theta_1 + \phi$ and of $\theta_2 - \phi$. Due to the design of the drive circuit to reverse the direction and stability of the motor movement, it is desirable for the driving phase difference $\theta_1 - \theta_2$ to be $\pi$. Therefore, the distance $L$ can be expressed as

$$2\phi + (\theta_1 - \theta_2) = 2(2n + 1)\pi$$

Then

$$L = \frac{4n + 1}{4} \lambda$$

When the frequency is 23 kHz and the wavelength $\lambda$ is 28 mm, the distance $L$ can be calculated to be 7, 35, 63,....

Fig. 5 SWR vs. the driving phase difference (SWR is Standing Wave Ratio. SWR of 1 means the traveling wave is generated perfectly.)
We investigated the condition in which the traveling wave can be generated experimentally with the structure shown in Fig.4. The vibration distribution along the bending bar was measured with changing the distance \( L \), and standing wave ratio (SWR) was calculated to evaluate the generation of the traveling wave. The SWR of 1 means the traveling wave can be generated perfectly without the reflections. The experimental results of SWR vs. driving phase difference \( \theta \) with various \( L \) are shown in Fig.5. The two small peaks in the SWR correspond to \( \theta_1 \) and \( \theta_2 \). From these results, the slider moves to right direction when the temporal phase difference \( T \) is 270 degrees, and moves to left when \( \theta_2 \) is 90 degrees. In this condition, the motor is driven with \( L \) of 63 mm, and this value of \( L \) corresponds to the theoretical value from eq.(3).

5. Propulsion characteristics

Three pieces of stainless steel plates was used as a slider as shown in Fig.1. The preload of 6 kPa between the slider and bending bars was applied by using the appropriate spring. With the driving voltage of 60 \( V_{pp} \) at 23 kHz to the two PZT elements, the slider moved in both directions with the stroke of 15 mm with the phase difference of 90 and 270 degrees. Fig.6 shows the transient response of the slider’s velocity. The maximum thrust \( F \) was measured from the transient rise response, and \( F \) can be expressed as

\[
F = M \frac{V_0}{\tau},
\]

where \( M \) is the mass of the slider, \( V_0 \) is the maximum velocity and \( \tau \) is the rise time[4]. From the experimental result of Fig.6, the maximum thrust \( F \) was calculated to be 78 mN.

We also examined the slider distance of the slider with changing the driving voltage and preload. The experimental results with several driving voltages are shown in Fig.7. With the larger driving voltage, the larger velocity of the slider also could be obtained. But with the driving voltage of 60 \( V_{pp} \), the PZT element was broken at \( t = 0.9 \) s due to high applied voltage.

Fig.6  The transient response of the slider’s velocity.
The sliding distance was measured with changing the preload to the slider with the driving voltage of 40 Vpp and the experimental result is shown in Fig.8. When the preload is more than the optimal value, the velocity of the slider decreases. The reason may be thought that the contact of the slider and the wave bottom of the traveling wave causes the backward thrust in the case of too much preload. The optimal preload is determined by the shape of the elliptic and the vibration displacement amplitude.

6. Conclusions

In order to design the traveling wave type ultrasonic linear motor with small volume, we investigated the structure using the resonance of the bar end, and obtained the optimal values of the length of the bar end, the driving frequency, the phase difference, and so on. We confirmed the movement to both directions of the slider with the maximum thrust of 75 mN and with the maximum velocity of 12 mm/s.

Reference

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