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Miniaturization of traveling wave ultrasonic linear motor
進行波型超音波リニアモータの小型構成の検討

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1. Introduction

Ultrasonic linear motors are classified into standing wave type and traveling wave type in terms of generating elliptical motion. Several standing wave types have been already put to practical use in precise moving tables and cameras. However, the life is limited because the contact area between the vibrator and the slider is small. On the other hand, it is not difficult to enlarge the contact area in the traveling wave motors since the elliptical motion is generated on the whole surface of the bar which guides the traveling wave.

In the original design of traveling wave type motor, the wave motion was excited using two Langevin transducers attached in right angle to the waveguide bar. This structure made it difficult to reduce the volume. We have already proposed the stator structure using two multilayered PZT elements between two parallel bending bars[1]. A new configuration to eliminate the bulky transducers is presented in this report. The method to excite traveling waves of bending vibration along a thin bar using small plates of piezoelectric ceramics bonded on the bar is discussed.

2. Configuration to excite a traveling bending vibration on a bar

The structure using PZT elements bonding to the both sides of a bending square bar is shown in **Fig. 1**. A pair of PZT plates sandwich the bar end work as a bimorph transducer since the strains induced in the PZT plates are opposite each other because of the directions of the poling and the applied electric field shown in the figure. **Figure2** shows an example of the results of the finite element analysis (FEA). At this frequency, 27.3 kHz, the transducers are operated in the bimorph mode efficiently and a bending wave with the wavelength of 48.4 mm is obtained.

3. Drive condition

In order to obtain a large thrust as ultrasonic linear motor, three following conditions are to be considered: 1) high electromechanical transformation efficiency of the transducer, 2) perfect traveling wave, in other words, lower standing wave ratio (SWR), and 3) optimal ratio of the transverse component to the longitudinal component in the elliptical motion.

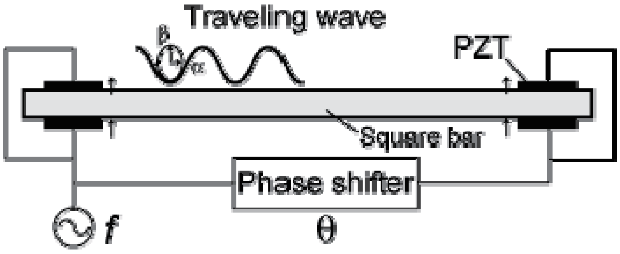

Fig.1 Structure with bimorph transducers

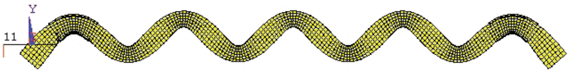

Fig.2 Bending mode with FEA at 27.3 kHz

First, let us consider the condition for exciting traveling waves when the bar is excited at the both sides with the bimorph transducers. There are two types of the phase differences, one is the spatial phase difference ϕ originated by the distance L between the two transducers, and the other is the temporal phase difference θ given by the phase shifter shown in **Fig. 1**. When the vibration amplitude excited by the transducer of the right side is expressed as

$$U_1(x,t) = U_0 \cos kx \cos \omega t \, , \qquad (3.1)$$

while the vibration amplitude excited by the transducer of the left side is expressed as

$$U_2(x,t) = U_0 \cos(kx+\phi)\cos(\omega t+\theta) \, . \qquad (3.2)$$

With these phase differences, the superposition of those two waves is rewritten as

$$\begin{aligned} U(x,t) &= U_1 + U_2 \\ &= U_0 \cos\left(\frac{\phi-\theta}{2}\right)\cos\left(kx-\omega t+\frac{\phi-\theta}{2}\right) \\ &\quad + U_0 \cos\left(\frac{\phi+\theta}{2}\right)\cos\left(kx+\omega t+\frac{\phi+\theta}{2}\right) . \qquad (3.3) \end{aligned}$$

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 one to the negative direction.

$$\theta-\phi = (2n+1)\pi \text{ or } \theta+\phi = (2n+1)\pi \qquad (3.4)$$

is the condition in which the traveling wave is generated between the two transducers because either term of the right side of (3.3) becomes 0. For the special case when the temporal phase difference is ±90 degrees, the distance L should be

$$L = \frac{4n+1}{4}\lambda . \tag{3.5}$$

Second, we also consider the shape of the elliptical motion. Transverse component α compared to the longitudinal component β is expressed as

$$\frac{\alpha}{\beta} = 2.33\sqrt{\frac{hf}{c_0}} \tag{3.6}$$

where h is the thickness of the square bar, f is the frequency and c_0 is the longitudinal sound velocity in solid. The relationship between α/β and h is summarized in **Fig.3** for the aluminum square bar. Referring to this graph, we determined the thickness h of 6 mm to make α/β near to 0.5. In order to obtain the velocity of the motor of 200 mm/s, the longitudinal vibration velocity should exceed this value.

4. Prototype

Utilizing the aluminum square bar whose length, thickness and width are 206, 6 and 6 mm, respectively, we prototyped the motor shown in **Fig.4**. The PZT elements, $15 \times 0.5 \times 10$ mm^3, polarized in the thickness direction, are bonded using epoxy. In this structure, the transducers are operated efficiently at 27.3 kHz, and the wave-length is 42.0 mm. The vibration distribution along the bending bar was measured by an LDV at the frequency with the temporal phase difference of 150 degrees, and the result is shown in **Fig.5**. SWR was calculated to be 2.1 and a traveling wave to the right direction could be obtained. The transverse component of 155 mm/s was achieved, so the longitudinal component is estimated to be 68.2 mm/s with eq.(3.4). When the bending bar was sandwiched with a friction contact, which consisted of two aluminum bars and rubber on its surface, the bending bar moved to right direction. The velocity was about 8 mm/s. With the temporal phase difference of 240 degrees, a traveling wave to the left direction could be also obtained, and the bending bar moved to the left direction with the velocity of about 9 mm/s.

5. Conclusion

We proposed the new structure for the ultrasonic linear motor with bimorph transducers. We succeeded to excite traveling waves in the both direction, and confirmed the movement of the slider at the velocity of 8 mm/s and 9 mm/s.

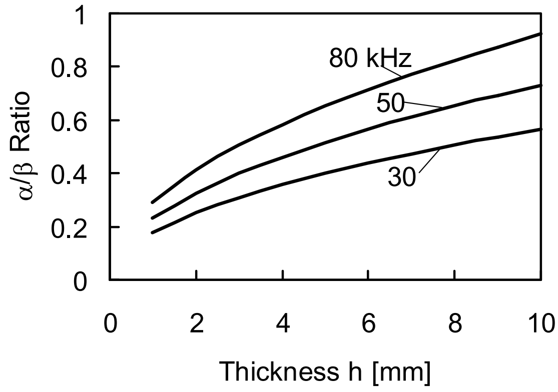

Fig.3 Ratio of the transverse component to the longitudinal component in the elliptical motion of the aluminum square bar.

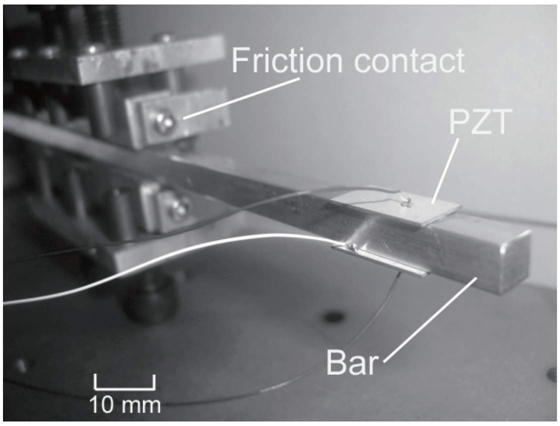

Fig.4 Prototype of the traveling wave type ultrasonic linear motor with bimorph transducer.

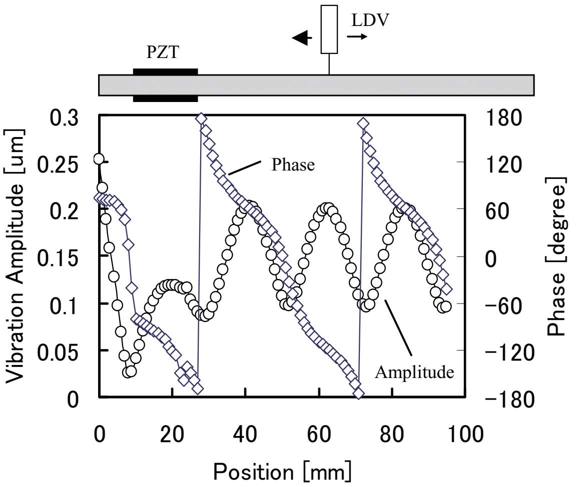

Fig.5 Vibration distribution along the bending bar at 27.3 kHz with the drive phase difference of 150 degrees.

References

1. H. Yamaura, K. Nakamura et al.: Proceedings of the Autumn Meeting of the Acoustical Society of Japan (Mar. 2008) 1231.