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Traveling wave excitation to a metal cylinder and application to object transport
金属円筒の進行波励振と物体搬送への応用

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1. Introduction

In traveling-wave type ultrasonic motors (TWUSMs), the traveling wave is excited to the elastic body, and the objects in contact with the surface of the elastic body are transported by the frictional force. The TWUSM has following advantages: noiseless, highly responsive, and excellent in controllability. Various shapes of ultrasonic linear motors (USLMs) have been studied[1)]. However, most USLMs require a linear guide, which complicates the structure. The use of a cylindrical stator eliminates the need for a guide and simplifies the structure. In addition, this types of USLMs are expected to utilize both inner and outer surfaces of the hollow cylindrical stator. In the previous study, the attenuation characteristic of the acrylic cylinder was used to generate a traveling wave in an axisymmetric longitudinal mode (L(0,1) mode) excited by the piezoceramic disc at the end of the cylinder, and the powder inside the hollow cylinder was transported.[2)] However, it is difficult to excite strongly because the acrylic cylinder is melted by the heat of the vibrator. On the other hand, a metal cylinder can be strongly excited, but the excitation method of traveling waves must be considered.

In this paper, two cylindrical piezoelectric vibrators were installed at both ends of a metal hollow cylinder, and the traveling wave excited by phase difference driving between both vibrators was confirmed, and a transfer experiment was attempted.

2. Vibration mode and operating principle

2.1 L(0,1) mode

Figure 1 shows the L(0,1) mode of cylinders. In L(0,1) mode, the distribution of radial and axial displacements is uniform on the circumference because there no axial nodal line. Therefore, the entire circumference can be used as the friction drive surface of the stator. In this model, two piezoelectric cylinder (PZT cylinder) are installed at the both ends of the metal cylinder to excite the L(0,1) mode by applying radial strain.

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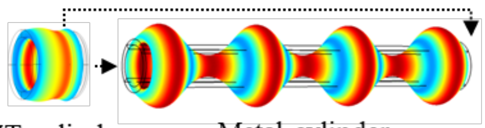

Fig.1 L(0,1) mode of cylinders.

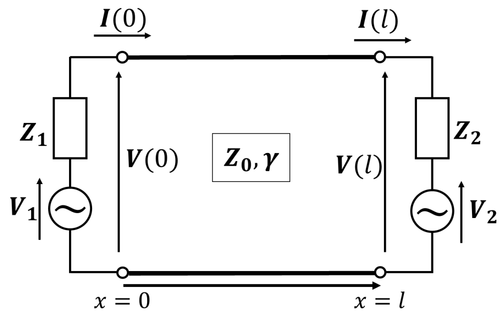

Fig.2 Electrical equivalent circuit for cylindrical stator.

2.2 Principle of traveling wave excitation

Figure 2 shows the electrical equivalent circuit for the cylindrical stator with dual excitation sources. The metal cylinder in which the L(0,1) mode is excited is considered to be equivalent to a one-dimensional transmission line of length l. In this transmission line, voltage $\boldsymbol{V}$ and current $\boldsymbol{I}$ correspond to force $\boldsymbol{F}$ and vibration velocity $\boldsymbol{v}$, respectively. $\boldsymbol{Z_0}$ is characteristic impedance, and $\boldsymbol{\gamma}$ is propagation constant.

The general solutions of the wave equation of this transmission line shown in Fig.1 are

$$\begin{cases} \boldsymbol{V}(x) = \boldsymbol{A}e^{-\gamma x} + \boldsymbol{B}e^{\gamma x} \\ \boldsymbol{I}(x) = \dfrac{1}{\boldsymbol{Z_0}}(\boldsymbol{A}e^{-\gamma x} - \boldsymbol{B}e^{\gamma x}) \end{cases} . \quad (1)$$

Here, the coefficient $\boldsymbol{A}, \boldsymbol{B}$ can be obtained by giving the boundary conditions at both ends of the transmission line ($x = 0, l$), and then voltage $\boldsymbol{V}(x)$ is obtained. Here, the amplitudes of the voltages $\boldsymbol{V_1}, \boldsymbol{V_2}$ are V_a, and the phase difference between $\boldsymbol{V_1}$ and $\boldsymbol{V_2}$ is ϕ. Furthermore, assuming that the internal impedances $\boldsymbol{Z_1}$ and $\boldsymbol{Z_2}$ are negligible and the transmission line is a lossless line, then, $\boldsymbol{Z_0} = j\beta$, where β is the phase velocity. The reflected wave

$\boldsymbol{V_r}(x)$ is expressed as

$$\boldsymbol{V_r}(x) = -\frac{V_a\left(e^{-j\beta l} - e^{j\phi}\right)}{e^{j\beta l} - e^{-j\beta l}} e^{j\beta x}. \qquad (2)$$

Therefore, the non-reflection condition is expressed as

$$\phi = -\beta l\,. \qquad (3)$$

When selecting $l = a\lambda$, where λ is the wavelength and a is real number, the relationship between l and ϕ can be obtained as

$$\phi = -2\pi a. \qquad (4)$$

If a is an integral multiple of $1/2$, from Eq.2, it will be in a resonance.

When l is extended by $\lambda/4$ from the resonance length, $\phi = -\pi/2$, and no reflected wave is generated.

3. Dual excitation drive experiment

3.1 Finite element analysis (FEA)

Figure 3 shows the model of the cylindrical stator. The stator consists of a metal hollow cylinder (SUS304, r_i: 14 mm, T_h: 2 mm, L_{st}: 138.8 mm) sandwiched between two piezoelectric cylindrical vibrators (C-213, FUJI Ceramics Co., L_{vib}: 14.94 mm). The metal cylinder and the two vibrators were bonded together with a 2.9 mm taper. Analysis using the FEA software (COMSOL Multiphysics 5.6) showed that the wavelength of L (0,1) mode excited by the metal cylinder at 96.3 kHz was approximately 32.7 mm. **Figure 4** shows the vibration mode of the cylinder with L_{st}: 130.6mm at a resonance frequency of 96.3 kHz. Adding the length $\lambda/4$ to the length of this resonance gave L_{st} 138.8mm, and the traveling wave was excited by driving with $\phi = -\pi/2$.

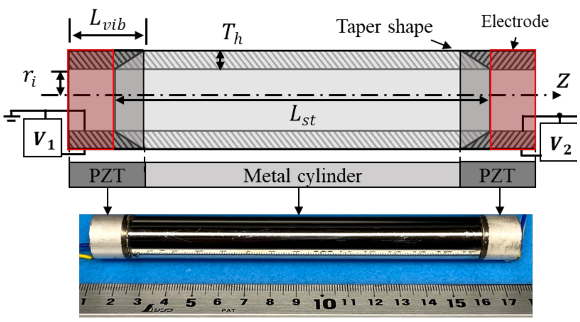

Fig.3 Model of cylindrical stator.

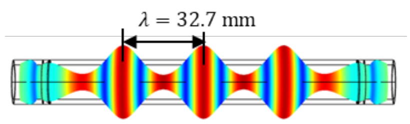

Fig.4 L (0,1) mode at 96.3 kHz.

3.2 Measurement result

Figure 5 shows the distribution of the radial vibration amplitude on the outside surface of the metal cylinder when $\boldsymbol{V_1} = \boldsymbol{V_2} = 15\mathrm{V_{pp}}$, $\phi = \pi/2$, and the excitation frequency of 99.15 kHz. A Laser Doppler vibrometer (LV-1800, ONOSOKKI) was used for the measurement. The measured and analyzed vibration amplitudes were normalized with the maximum value (measurement: 40.1 nm, analysis: 49.3 nm). The standing wave ratio (SWR) was approximately 1.72, indicating that the reflected wave was reduced.

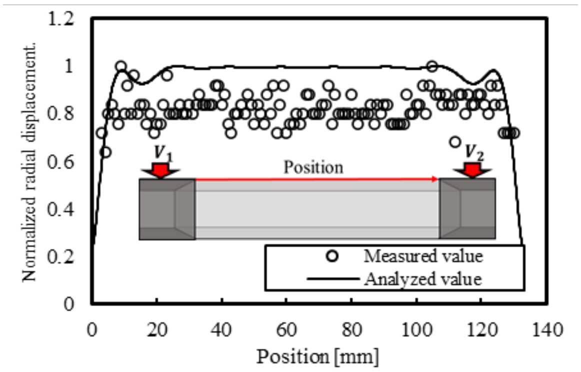

Fig.5 Radial displacement of cylinder

3.3 Transport experiment

Figure 6 shows the time-varying state of a slider transportation. When the applied voltage $\boldsymbol{V_1}, \boldsymbol{V_2}$ were $60\,\mathrm{V_{pp}}$, $\phi = \pi/2$, the excitation frequency was 99.15 kHz, and 8.5 g slider was smoothly transported by exciting the traveling wave. The maximum speed of the slider was 9.1 mm/s. The slider was made of three metal rings

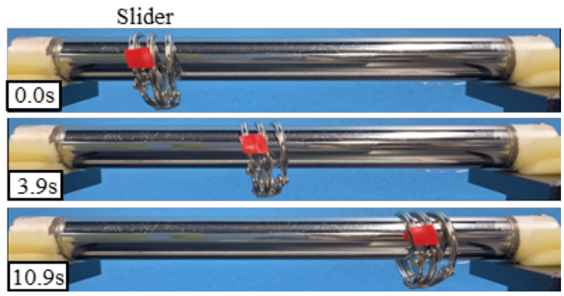

Fig.6 State of slider transportation.

4. Summary

The traveling wave in L(0,1)mode on the cylinder was excited by dual vibration sources which were arranged at both ends of the metal cylinder and which were excited with the phase difference according to the length of the cylinder. In addition, the slider could be transported by contact.

References

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