Hybrid Transducer Type Ultrasonic Linear Motor

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Hybrid transducer type ultrasonic motors have the advantage of freedom of design. A linear motor of this type consists of a longitudinal vibrator and multilayered piezoelectric actuators. The transducer is operated at the resonance frequency of the vibrator. In this paper, the characteristics are measured in a study of the basic operating conditions, and a maximum speed of 50 cm/s, maximum force of 500 gf and maximum efficiency of 36% are recorded. It is believed that performance can be improved by theoretical studies.

§1. Introduction

A traveling wave type ultrasonic linear motor has a large vibration system which requires a high power electric source. The amount of power consumed by the vibration system is so great that highly efficient performance is difficult. To realize a high performance ultrasonic linear motor, the vibration system must be compact.

A hybrid transducer type ultrasonic motor, on the other hand, can be designed in a variety of ways. The hybrid transducer for a linear motor is constructed using a longitudinal vibrator and multilayered piezoelectric actuators, which are driven at the resonance frequency of the vibrator. The actuators are thus operated at a non-resonance frequency, making tuning of the resonance frequencies of the two parts unnecessary.

Here we report experimental studies on basic data for the operation of the hybrid transducer type ultrasonic motor and measurements of the characteristics of the motor.

§2. Principle and Configuration

2.1 Principle

The hybrid transducer for an ultrasonic linear motor consists of a longitudinal vibrator and multilayered piezoelectric actuators, as shown in Fig. 1. The transducer is pressed against a rail. The longitudinal vibrator is operated at its resonance frequency and the two actuators are operated at the same frequency, which is not their resonance frequency. The vibrator and the actuators have individual electric driving sources, and the phase between these two sources is shifted to achieve optimum operating condition of the motor.

The operating sequence is shown in Fig. 1. The vibrator and actuators are operated as follows:

(1) Vibrator: extensional vibration velocity is maximum.
   Actuators: the left hand one is extended so that it contacts the rail; the right-hand one is shortened and away from the rail. The longitudinal vibration is transformed to a righthward linear motion.

(2) Vibrator: stretched, making the vibration velocity null.

(3) Vibrator: vibration velocity in the opposite direction to (1) is maximum.
   Actuators: the left-hand one is shortened and the right-hand one is stretched to contact the rail.
   As in (1), vibration is transformed to rightward linear motion.

(4) Vibrator: shortened, making the vibration velocity null. Actuators and the transducer are same as (2).

By repeating sequences (1) to (4), the vibration motion of the longitudinal vibrator is transformed to a linear one-directional motion. If the driving source phase of the vibrator or the actuators is inverted, the linear motion is reversed.

The hybrid transducer type ultrasonic motor is designed so that the vibrator generates the mechanical force for the linear motion and the actuators control the frictional force. This design is appropriate for ultrasonic motors because a large quantity of mechanical output power must be efficiently transformed through vibration, and friction control does not require much power or high amplitude, only large force and low input power.
The velocity for this motor can be controlled simply by adjusting the vibration velocity of the longitudinal vibrator. As shown in Fig. 2, the amplitude of the actuators has, in principle no influence on the motor velocity. The motion of the motor is therefore stable down to a very slow speed if the vibration amplitude of the actuators is kept constant.

2.2 Trial motor

A trial hybrid transducer is shown in Fig. 3. The longitudinal vibrator is a bolted Langevin type transducer 20 mm in diameter and 83 mm in length. It has four PZT elements 2 mm in thickness and sandwiched by two duralumini columns. In the state of which the actuators are attached with adhesive, the resonance frequency of the vibrator is 31.3 kHz, Q factor 420, $Y_{mm}$ 14 mS and force factor 0.32 N/V. Maximum vibration velocity is more than 0.5 m/s. The multilayered piezoelectric actuators are $5 \times 5$ mm$^2$ in square cross section and 4.5 mm in height. The layered part is 3.3 mm and layered number is about 30. The displacement per unit voltage of these elements is 0.03 μm/V and the force factor is 8.6 N/V. Total weight of this hybrid transducer is 95 g.

The transducer is assembled onto a linear motor as shown in Fig. 4, and is held with its flange by a holder, so that the actuator surfaces uniformly contact the steel rail. The holder is thrust upward and the static pre-load is applied by a spring.

§3. Operation Condition

Driving electric sources of the vibrator and the actuators have an optimum phase shift between them. If the contacting time of the actuators with the rail is short enough, the optimum phase shifts are 0 and 180 degrees, this is because the vibration velocity of the vibrator is in phase with the driving current, and the displacement of the actuators is in phase with the driving voltage. Since the contacting time is actually finite, however, it was found experimentally that the optimum phase shifts were between $0^\circ$ to $10^\circ$ and $-170^\circ$ to $-180^\circ$ as shown in Fig. 5. During the experiment, the driving voltages of the vibrator and the actuators were kept constant, while the phase shift of the voltage of the actuators against the driving current of the vibrator was varied. Results showed that the hybrid transducer type ultrasonic linear motor operates as expected.

The dependency of the motor velocity on the driving voltage of the actuators is shown in Fig. 6. The driving voltage of the vibrator was fixed at about 15 V$_{rms}$ and the driving voltage of the actuators was varied. The velocity ratio, that is, the vibration velocity to the motor velocity, was then plotted. If the applied voltage to the actuators is relatively small, the contact time is long. Thus the slip between the actuators and the rail increases, so the velocity ratio becomes less. With an increase in applied voltage, the velocity ratio reaches unity. Here, if the pre-load is
1.1 kgf, the velocity ratio is above unity because of the flexural vibration of the actuators.

It was observed that the driving current of the vibrator was distorted as illustrated in Fig. 7. The crest of the waveform was compressed owing to its contact with the rail.

§4. Performance of the Motor

The linearity of velocity against the driving current of the vibrator was studied. The voltage applied to the actuators was fixed at 12.7 V$_{mn}$ and the pre-load was varied at 0.7 kgf, 2.2 kgf and 4.4 kgf. As can be seen from the results in Fig. 8, the proportionality was good and the linear range was relatively large.

An example of the characteristics of the mechanical load versus slider velocity is shown in Fig. 9. The velocity decreases linearly with increasing mechanical load as in other types of ultrasonic motors. The input power also decreased since the driving voltage of the vibrator was maintained constant during the experiment. This indicates that the motional impedance of the vibrator increases with increasing mechanical load of the motor. For high efficiency operation of the vibrator, a relatively large mechanical load is required. This is therefore a desirable phenomenon to assure efficient motor operation, since the load of the motor acts as the mechanical load on the vibrator.

The maximum efficiency of the motor, namely, (mechanical output power)/(electric input power to the vibrator), was 36%. Here, in calculating the efficiency, the applied power to the actuators was ignored. Since this power is not transduced to the mechanical output of the motor, the level of power must be low. However, the input power of the actuators of this motor is of almost the same order as the driving power of the vibrator, because the piezoelectric material of the actuators is not conducive to high frequency vibrations and thus the dielectric loss is large. To correct this requires improvement in the actuators.

In other operating states, a maximum output mechanical force of 500 gf and maximum velocity of 50 cm/s were recorded.

§5. Discussion and Conclusion

A trial hybrid transducer type ultrasonic linear motor was fabricated and the basic factors of its operation were confirmed. The output force is still small and should be enlarged by increasing the pre-load. Performance of the longitudinal vibrator indicates that a maximum output force of 5 kgf or more should be achievable.

The problem is whether the actuators can generate enough force against so large a pre-load. The actuators used here may not have enough capability and a large cross section element made of material more appropriate for high frequency vibrations may be required.

There were also problems in the design of the hybrid transducer: the flexural vibration of the actuators should be suppressed, which would improve the stability of the motor operation.

To improve the overall performance of the motor, the mechanism of the conversion from vibration to linear motion should be quantitatively studied.

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References

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