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Wireguide driving actuator using resonant-type smooth impact drive mechanism

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ABSTRACT

This paper proposes a wireguide-driving piezoelectric actuator for narrow space driving such as in endoscopic devices. Conventional wireguide-driving actuators use torsional or bending vibration. We examined a resonant-type smooth impact drive mechanism (R-SIDM) utilizing longitudinal vibration as the driving principle. The longitudinal vibration is resistant to outside disturbances. Different to conventional smooth impact drive mechanism (SIDM) actuators, R-SIDM actuators use the resonant effect. The quasi-saw-shaped displacement is excited by combining two resonant vibrations with a frequency ratio of 1:2. This driving principle allows lower input voltage compared to that of the conventional SIDM. As the driving source, a step-shaped Langevin transducer was fabricated. With this step-shaped design, the longitudinal resonant frequency ratio f_3/f_1 could be adjusted to 2. At the tip of this transducer, an aluminum wireguide was attached to excite a quasi-saw-shaped vibration at the end tip. The length of the wireguide was designed to match the resonant frequencies of the transducer. It was confirmed that a bearing rotor (diameter: 10 mm) could be rotated. As we expected, a quasi-saw-shaped vibration was excited, and we could measure a non-loaded driving speed of 176 mm/s and a maximum load of 0.47 N for a 100 V_{p-p} input voltage and a 6.0 N preload.

1. Introduction

Piezoelectric motors have a high power-density with a simple configuration and compact size [1–3]. In addition, by transmitting vibration energy along a flexible wireguide, remote actuation becomes possible. The driving point is at the tip of the wireguide; therefore, it is able to be located far from the vibration source (the piezoelectric transducer). Such a configuration would be useful for manipulation in their extreme environments, such as high or low temperatures, vacuum conditions, or for operations on the human body.

One of the advantages of remote actuation is that a large transducer (high-power source) can be utilized, and this high power can be used for a small rotor or a slider operation in a narrow area at the tip of the wireguide.

Until now, few research studies on remote wireguide operation have been reported. Usually, the bending vibration is transmitted along a thin wire, and at the tip, a rotational motion is obtained [4,5]. In this manner, the bending vibrations would be damped easily by being touched from the outside. A torsional vibration mode was also examined for this concept [6–8], however, the output force was not sufficient. This insufficient torque was due to the small size of the transducer.

In this study, we describe a motor, whose rotor is driven based on the principle of the resonant-type smooth impact drive mechanism [9–11] (R-SIDM) at the tip of a flexible aluminum wireguide attached to a Langevin transducer. On the following we will describe the motor's driving principle, its design and characteristics.

2. Driving principle

2.1. Principle of the resonant-type smooth impact drive mechanism

The SIDM [12] actuator is a piezoelectric linear actuator, and its principle driven with low frequency operation is shown in Fig. 1. The stator movement is composed of two successive movements: a slow forward movement and a rapid backward movement. From (i) to (ii) in Fig. 1, the stator moves forward slowly. At this time, the slider moves together with the stator due to the frictional force (stick motion). In contrast, from (ii) to (iii), the stator moves

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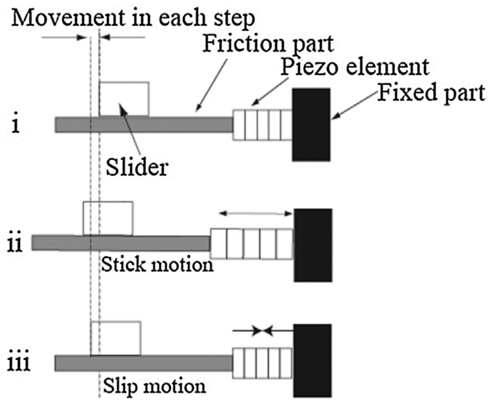

Fig. 1. Principle of the SIDM actuator driving with low frequency operation (stick slip motion).

backward rapidly, and this makes the slider slip due to the inertia force (slip motion). This slip motion corresponds to one step movement. By repeating these movements, the slider is driven to the left. With the reversed movement of the stator in time (meaning the rapid forward and slow backward movements), the slider driving direction can be reversed to the right. Increasing the driving frequency of the saw-shaped movement, this stick-slip driving changes to a slip-slip motion; however the driving direction is the same because the driving duration for slow movement is larger than that for rapid movement.

Since the conventional SIDM actuators utilize non-resonant vibration, a high voltage is required, which results in heat generation. In the previous study, we proposed the R-SIDM actuator [9–11] to solve this problem. Differently from a conventional SIDM actuator, the R-SIDM actuator utilizes a quasi-saw-shaped displacement by combining two excited sinusoidal vibrations whose frequency ratio is 1:2. This R-SIDM driving principle enables low input voltage operation.

2.2. Design of a step-shaped Langevin transducer

We adopted a Langevin transducer as the driving source to achieve high-power driving. The symmetrical shape was introduced to simplify the adjustment of the resonant frequency ratio and to fix the transducer at the nodal point [10]. The ratio of the fundamental (f_1) and third resonant frequencies (f_3) becomes 1:3 if the transducer has a simple cylinder structure. To control this ratio to 1:2, a step structure was designed at the metal block portion, as shown in Fig. 2.

Four hard-type PZT (Fuji-ceramics C-203) rings (thickness: 3 mm, outer diameter: 15 mm, inner diameter: 8 mm) were bolted with duralumin rods (length: 46 mm). The polarization of the PZT rings was aligned to the thickness direction, and each polarization direction was opposite to the neighboring rings. The diameter of the duralumin rods was 15 mm on the center side and 7 mm on the tip side of the step structure.

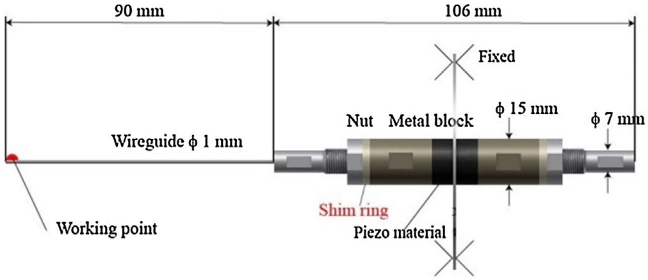

Fig. 2. Shape of the designed step-shaped Langevin transducer.

The resonant frequency ratio (f_3/f_1) is a function of the structural parameters, such as the diameter ratio between the center side and the tip side of the step structure. The position of the step structure can also affect the resonant frequency ratio [10]. The Langevin transducer has high Q_m and the resonant vibration can be excited in the quite narrow frequency range. Therefore, we controlled the step position precisely by inserting shim rings to adjust the resonant frequency ratio. The shim rings were made of steel (SUS304), and various thickness shim rings from 0.1 mm to 1 mm were prepared.

We determined the optimum step position by calculating transfer matrix [13]. When the step position is 25 mm from the center, the relationship between the added shim rings' thickness and the resonant frequency ratio (f_3/f_1) was calculated, as shown with the line labeled as "calculated" in Fig. 3. This graph shows that f_3/f_1 becomes 2 when 5 mm shim rings are inserted. The resonant frequencies were calculated to be 32.2 kHz for f_1 and 64.4 kHz for f_3.

2.3. Design of the wireguide

This study proposes a frictional drive at the tip of the flexible aluminum wireguide whose diameter is 1 mm. When the Nth resonant frequency of the wireguide is the same as that of the step-shaped Langevin transducer (f_1), the 2 Nth resonant frequency of the wireguide matches f_3. This is because the ratio of the Nth and 2 Nth longitudinal resonant frequency of the simple wire-bar is 1:2 under the free–free boundary condition. The frequency ratio of the step-shaped Langevin transducer is also 1:2, as mentioned before for R-SIDM driving. From the sound velocity in aluminum (5100 m/s) and the calculated values of f_3 and f_1, the wireguide length was calculated to be an integral multiple of 79.3 mm.

To confirm the longitudinal vibration mode of the Langevin transducer and the 79.3 mm wireguide, the transfer matrix was calculated. This wireguide length corresponds to $N = 1$ (79.3 mm). The boundary condition was free–free. For the modal analysis, the vibration loss was taken into consideration as imaginary part stiffness that is 0.1% of the real part stiffness for all components. The mode shape for f_1 is shown in Fig. 4(a), and that for f_3 is in Fig. 4(b). The horizontal axis represents the position from the center of the Langevin transducer. The vertical axis represents the normalized velocity since the Q_m value was not revealed before manufacturing the stator transducer.

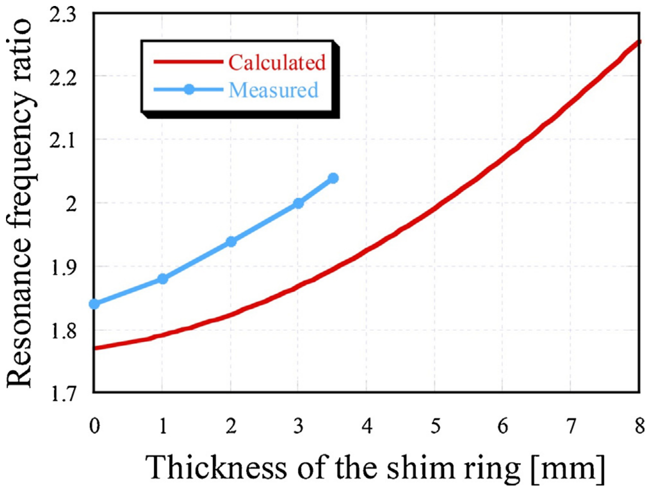

Fig. 3. Relationship between the thickness of the shim ring and the resonant frequency ratio.