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Temperature Compensation of Ultrasonic Transducer Using Dynamic Resonant Frequency Control
動的共振周波数制御による超音波振動子の温度補償

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1. Introduction

Some ultrasonic transducers are operated in multiple vibration modes to improve output performance or achieve specific motions.[1-2] For such operation, a constraint on the frequency ratio of different modes is necessary. However, due to the high quality factor, the resonant frequencies and resonant frequency ratio change easily with the operating condition (especially the temperature) change. Therefore, dynamic resonant frequency control for multimodal piezoelectric transducers is extremely significant to stabilize their performance.

In this study, a dynamic resonant frequency control method[3-4] has been improved for two vibration modes' resonant frequency ratio and velocity ratio control. Temperature compensation of the ultrasonic transducer's resonant frequency ratio was realized through this method, and a quasi-sawtooth waveform was obtained and maintained at various conditions.

2. Control Method

A step-shaped Langevin transducer working at both first and third longitudinal modes is shown in **Fig. 1**. Apart from the driving PZTs, passive PZT is deployed and connected to a MOSFET switch. By turning on and off this switch, the passive PZT's boundary condition is varied between short and open, electrically. The stiffness of these parts changes between c^D and $c^E = c^D/(1-k^2)$, where c^D and c^E are the stiffness in open and short conditions, respectively, and k is the electromechanical coupling factor. As a result, the MOSFET switch can dynamically control the resonant frequency by changing the control signal's duty ratio and phase.

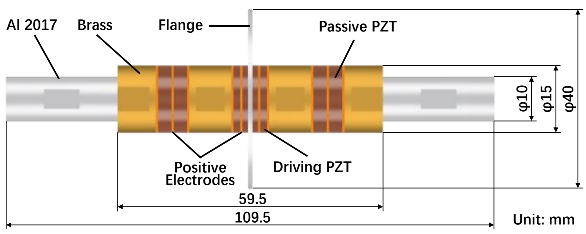

Fig. 1 Step-shaped Langevin transducer with passive PZT parts.

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When operating, the resonant frequency ratio of the transducer's third and first modes should be 2:1. In this case, driven by two sinusoidal voltages, the transducer works at both modes, and a non-sinusoidal waveform can be output. Here, the target waveform is quasi-sawtooth, so the vibration velocity ratio of the third and first longitudinal modes should be 1:2.

Through deliberate design, the passive PZT parts were deployed at the node positions of the third mode, so the passive PZT barely changes the third mode's resonant frequency but only adjusts the first mode's frequency, and the frequency ratio is controlled. A prototype of the transducer was fabricated and tested with a Laser Doppler vibrometer (LDV), according to the velocity frequency response at open and short conditions, the third mode resonant frequency was around 48kHz, and the frequency ratio between the third and first modes was obtained, as shown in **Fig. 2**. With the temperature increasing to 80℃, the target frequency ratio of 2:1 was in the reachable band.

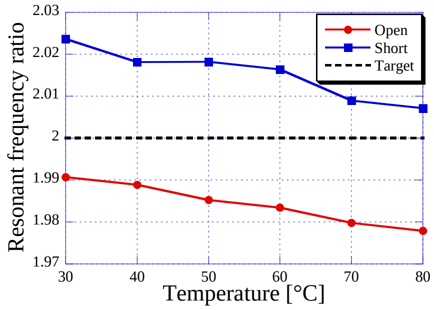

Fig. 2 Temperature characteristic of resonant frequency ratio between the third and first modes at open and short conditions.

3. System Configuration

A dynamic resonant frequency control system was established based on this proposed control method, as shown in **Fig. 3**. A function generator (NF Corp., WF1968) generates two sinusoidal driving voltages with a frequency ratio of 1:2, and these voltages are amplified by a high-speed amplifier (NF Corp., HSA4011) for driving the transducer. This function generator also provides the square switching signal to the MOSFET switch, which is synchronized to the first driving frequency.

An LDV (Polytec, NLV-2500) is employed to measure the vibration velocity. Then, the measured first mode's velocity phase, third mode's velocity phase, and velocity amplitudes are obtained by the three lock-in amplifiers (NF Corp., LI5640). All equipment is controlled by a computer with GPIB communication.

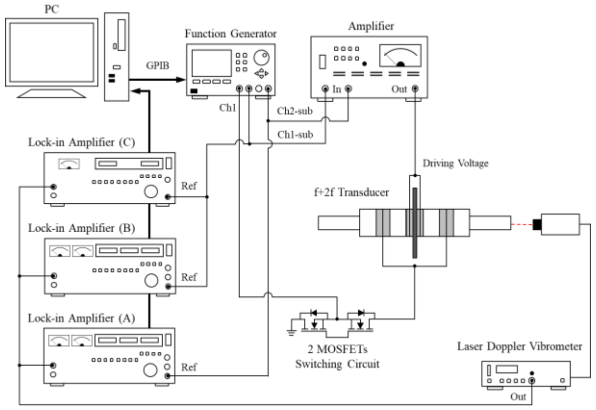

Fig. 3 Configuration of the dynamic resonant frequency control system.

4. Experiment results

The experiment was carried out through this proposed control system to realize temperature compensation of the resonant frequency ratio.

During the control, the resonant state was estimated by the phase difference between the velocity and driving voltage. When this velocity phase is close to 0, the transducer is in resonant. Firstly, the third mode driving frequency was swept with a step of 1Hz to match the third mode resonant frequency, and the first mode driving frequency was half of the third mode's frequency. Then, through proportional feedback control of the switching duty ratio for the MOSFET switch, the first mode resonant frequency was controlled to match the first driving frequency. As a result, the velocity amplitudes of both modes could be adjusted by proportional control to approach the velocity targets (50mm/s and 25mm/s, respectively).

After controlling, a quasi-sawtooth wave was obtained and maintained even with the temperature increasing from 30 to 70°C, as shown in **Fig. 4**.

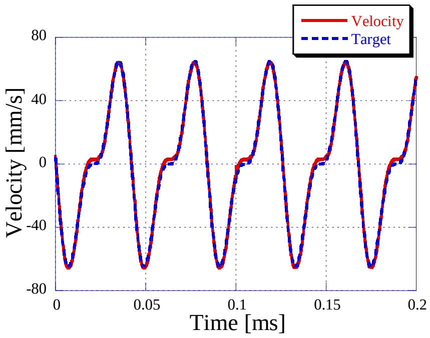

Fig. 4 Measured vibration waveform and the target synthetic waveform at 30°C.

The third mode resonant frequencies before and after control at various temperatures are shown in **Fig. 5**. The resonant frequencies changed linearly with the increase in temperature. The frequencies were a little lower after control. This is because the passive PZT parts were not precisely deployed at the third mode nodes of the fabricated transducer, so the third mode resonant frequency was still slightly affected by the open and short conditions.

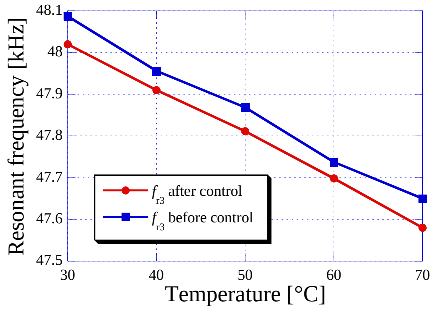

Fig. 5 Third mode resonant frequencies before and after control at various temperatures.

The velocity phases of the first and third modes at 70°C are shown in **Fig. 6**. It took around 80s to reach the target waveform. By optimizing the control parameters like proportionality constant and waiting time for each operation, there is much room to shorten the control time further.

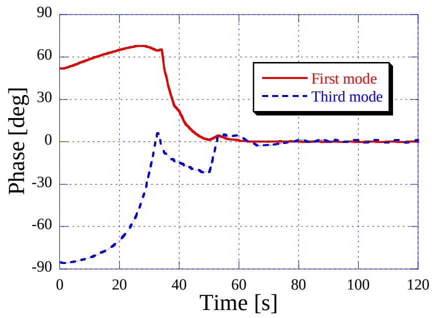

Fig. 6 Phase difference of the vibration velocity and driving voltage during the control at 70°C.

5. Conclusions

Temperature compensation of a Langevin transducer's resonant frequency ratio was realized through the dynamic resonant frequency control method, and a quasi-sawtooth waveform was obtained and maintained at various conditions.

References

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