Lead-Free 4 Layered Piezoelectric Motor

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Abstract

In this paper, we present a four-layered, lead-free piezoelectric ultrasonic actuator integrated into a precision test stage. The motivation for developing lead-free piezoelectric actuators stems from the toxicity of lead in conventional lead zirconate titanate (PZT) actuators and from European RoHS regulations, under which the current exemption for PZT is under evaluation. However, the mechanical performance of lead-free bulk piezoelectric actuators remains challenging. The reduced efficiency of the actuator leads to excessive heat generation during operation, which limits performance reliability and motion stability under continuous drive at high duty cycles. To mitigate heat generation, we propose a novel actuator structure composed of four layers of lead-free piezoelectric plates bonded with elastic elements. These elements were designed not only to enhance thermal conductivity but also to incorporate a cavity structure that enables rapid heat dissipation for cooling. The cavity-embedded elastic elements were optimized to provide ideal clamping conditions for the actuators, minimizing oscillation amplitudes and thereby reducing mechanical losses.

Lead-Free, Piezoelectric Motor, Layered Structure, Cavity Elastic Elements

1. Introduction

There are several reasons for developing lead-free ultrasonic motors. First, piezoelectric ultrasonic motors using lead-free ceramics may become mandatory in the near future due to the well-known toxicity of lead. Second, the European RoHS exemption for PZT at the end of 2027. Third, an environmentally friendly production process for lead-free materials that minimizes the volatilization of toxic substances during calcination and sintering would be desirable. Finally, the disposal of lead-based piezoelectric materials is a major concern for PZT-based ceramics [1].

The performance of piezoelectric motors built with lead-free actuators is significantly lower than that of their PZT-based counterparts [2]. In addition to the lower d_{33} piezoelectric constants, heat generation in lead-free actuators poses a major challenge for achieving stable, reliable, and robust resonant drive in lead-free piezoelectric-motor stages [3-4]. The problem arises because the eigenfrequency of the motor shifts dramatically during operation.

This paper presents a lead-free piezoelectric motor constructed from four ceramic layers to reduce both the required voltage and the heat generation. Lead-free piezoelectric layers used in this actuator are based on copper-doped potassium sodium niobate (KNN) ceramics [5]. PIC GmbH (Lederhose, Germany) produced piezoelectric ceramics with dimensions of 25 mm × 11 mm × 1 mm that were used to fabricate composite-layered PILine® actuators by embedding elastic elements. The motion controller used for the performance test is the C-867.2U2, a piezoelectric motor controller for PILine® systems with PID (Proportional-Integral-Derivative) adaptive motion control. Various driving methods, such as single-source, dual-source, and dual-frequency excitation, which have been implemented for standard PILine® systems, can also be applied to this structure [6–7].

2. Design of piezoelectric motors

Four-layered, lead-free ceramics were bonded to cavity-embedded elastic elements, made of copper and an alumina pusher, forming the contact element. This arrangement is illustrated in a CAD model and in a prototype showing the ideal clamping positions with minimized oscillation amplitudes (Figures 1 and 2).
A four-layered lead-free actuator in metal housing was built and preloaded against friction bar of the stage (Figure 3).

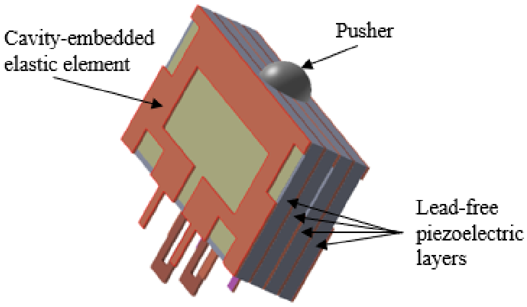

Figure 1. Four-layered lead-free actuator, CAD model.

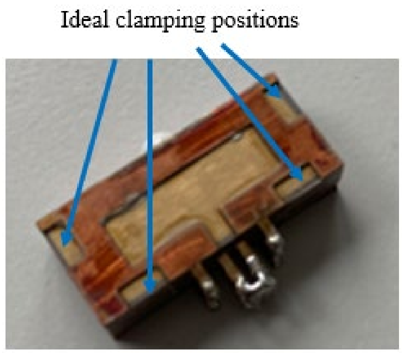

Figure 2. Four-layered lead-free actuator, prototype.

The change in eigenfrequency during the burn-in test was measured. The required motor voltage at the start of operation did not increase significantly when the excitation frequency was between 194 and 196 kHz. After ten minutes of operation, the motor output remained stable, which can be attributed to improved thermal conductivity from the composite design and the cavities between the layers. Burn-in measurements indicate that operation between 194 and 196 kHz is the optimal frequency range for continuous drive of the layered lead-free piezoelectric stage.

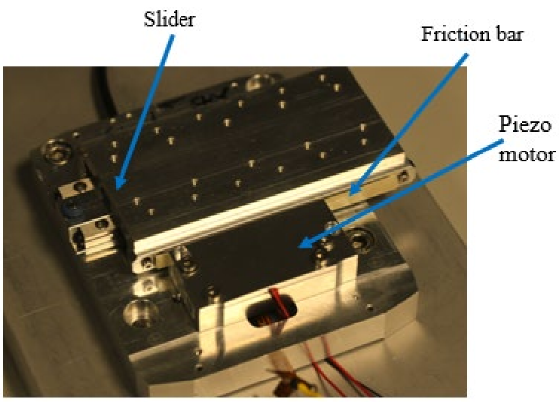

Figure 3. U-551K005 stage built with four layered lead-free piezoelectric motor.

3. Experiments and results

The test stage with four-layered lead-free actuators was evaluated for impedance change, voltage requirement in auto-frequency mode, continuous drive in fixed-frequency mode, push/pull force, and current requirements.

3.1. Impedance measurements

The dynamic characteristics of the lead-free layered actuator were also examined with an impedance analyzer. The actuator was soldered to flexible cables and mounted on the stage with a 10 N preload. Using a small-signal impedance analyzer (Keysight, E4990A), the actuator's eigenfrequency was measured to be 194.3 kHz (Figure 4).

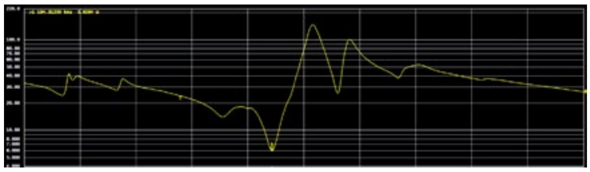

Figure 4. Impedance measurement.

3.2. Voltage requirement in auto frequency mode

The test stage equipped with the lead-free actuator was driven continuously in auto-frequency mode, in which the controller's driver unit determined the optimum operating frequency for the piezoelectric ceramics. The auto-frequency search bandwidth was set from 192 to 196 kHz. The required voltage (blue) and the optimum frequency (orange) as functions of operation time are plotted in Figures 5 and 6.

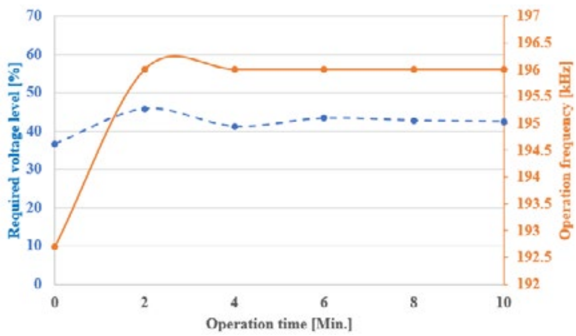

Figure 5. Voltage requirement and optimum operation frequency from controller over continuous drive during closed-loop velocity with 20 mm/s.

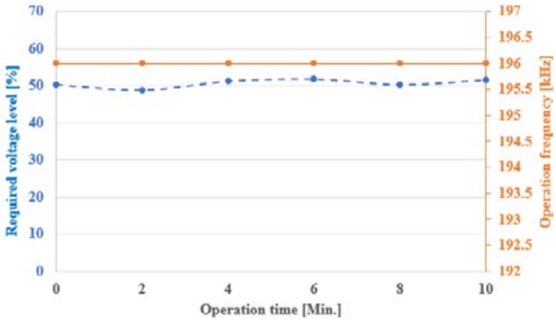

Figure 6. Voltage requirement and optimum operation frequency from controller over continuous drive during closed-loop velocity with 40 mm/s.

As shown in the figures, the motor output required for the velocity settings of 20 mm/s and 40 mm/s remained below 60 % of the maximum allowable voltage supplied by the controller during ten minutes of continuous operation. The optimum frequencies largely rose to the maximum value during operation; consequently, the optimum frequency was fixed at the maximum value, 196 kHz. This corresponds to fixed-frequency operation for continuous drive.

The continuous drive of the stages without the auto-frequency mode was tested with a closed-loop velocity of 20 mm/s. The frequencies chosen for this test ranged from 196 kHz to 198 kHz. The required voltage levels for various fixed-frequency settings over a 10-minute operation time are plotted in Figure 7.

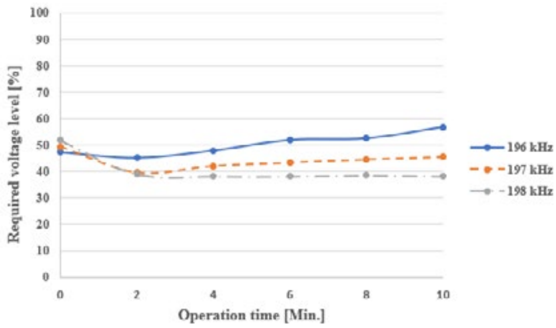

Figure 7. The required voltage level with various fixed frequency settings for a 10-minute operation time.

The motor output at the start of operation did not increase significantly when the frequency was between 196 kHz and 198 kHz. After ten minutes of operation, the motor output remained constant, which could be attributed to improved thermal conductivity of the structure due to the composite design and the cavities between the layers. Measurements showed that operation frequencies in the 196–198 kHz range could be used as the optimum frequencies for the continuous drive of the lead-free layered piezoelectric stage.

3.3. Push/pull force with fixed frequency operation

As shown in Figure 8, the push-pull force capacity of the layered lead-free test stage against gravity was measured using a rope roller mechanism with dummy loads.

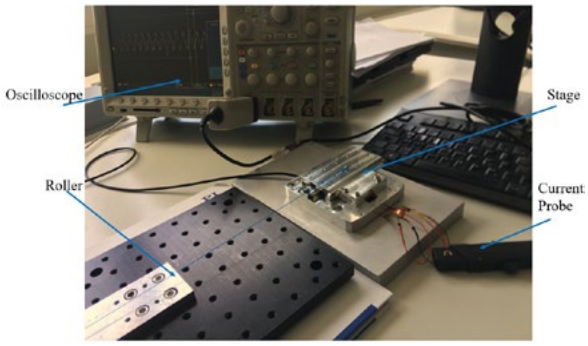

Figure 8. Test setup to measure push/pull force capacity and current requirements during closed-loop operation.

The U-551K005 stage with a four-layered lead-free actuator can handle a push-pull force of 4 N at closed-loop speeds of 10 mm/s, 20 mm/s, 40 mm/s, and 60 mm/s, operating at frequencies of 192 kHz and 194 kHz, as shown in Figure 9. For this stage, the required voltage remained below 70 % of the maximum voltage supplied by the controller.

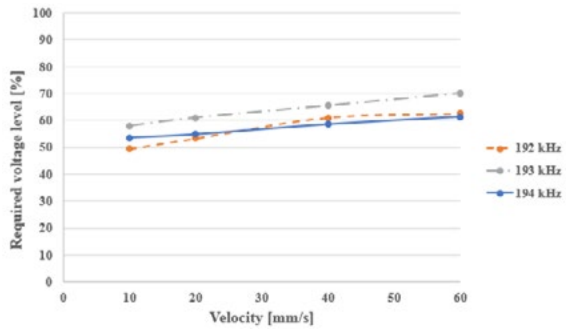

Figure 9. Required voltage at various closed-loop velocities and operation frequencies against 4 N push/pull force against gravity.

Figure 8 shows that a TCP0030A (120 MHz) current probe was used for the measurements. Figure 10 presents the current requirements at various velocities when the stage moved against 4 N push/pull force against gravity, respectively. The motor operated at 193 kHz.

Current measurements confirmed that the required current remained below 1000 mA (1 A), in line with the specifications of the C-867.2U2 controller. Although layered actuators demand higher current, the measured values are still compatible with standard controllers.

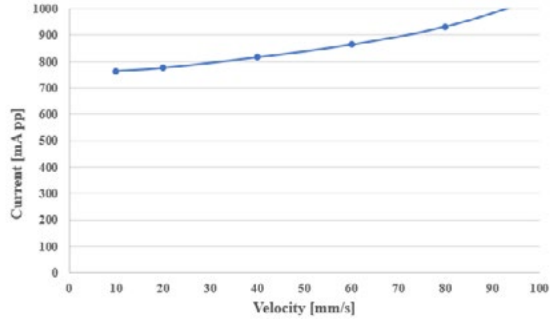

Figure 10. Motor current measurements at various velocities when it is 4 N loaded.

3.4. Life-Time test

A layered lead-free actuator-based stage was tested at a velocity of 10 mm/s for more than 80 days as part of a compact life-time test. As shown in Figure 11, the stage remained stable over days of operation. There was no degradation in voltage levels over the lifetime. Additionally, there was no excessive heat generation during operation, since the stage operated at moderate voltage levels with fixed frequencies of 194 kHz and 195 kHz.

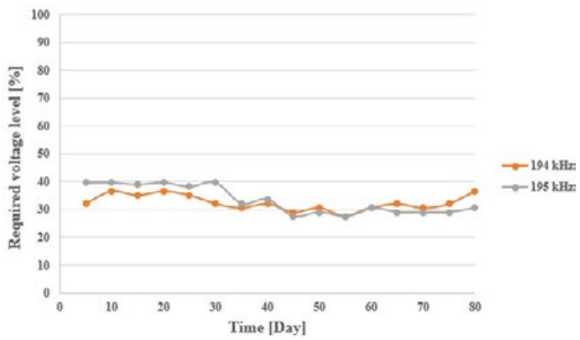

Figure 11. Life-time test for four-layered lead-free actuator at two operation frequencies.

4. Conclusion

In this paper, we tested four-layered, lead-free actuators in a composite structure. The actuator, composed of four lead-free ceramic plates bonded to cavity-embedded elastic elements, was housed in a metal casing and preloaded against a friction bar mounted on the stage.

The eigenfrequency shift during operation was measured. Results showed that the required motor voltage during the burn-in phase did not increase significantly when the excitation frequency was maintained between 194 kHz and 196 kHz. After ten minutes of operation, the motor output stabilized, which can be attributed to the improved thermal conductivity of the composite design and the cavities between the layers.

Push-pull force measurements showed that the test stage equipped with four-layered, lead-free actuators could deliver a 4 N push/pull force against gravity at closed-loop velocities up to 60 mm/s, operating at driving frequencies of 192–194 kHz. During closed-loop operation, the required voltage remained below 70 % of the controller's maximum supply voltage.

As previously observed, self-heating in lead-free bulk piezoelectric ceramic actuators during continuous operation raises their eigenfrequency. Consequently, auto-frequency mode is unsuitable for stages based on lead-free bulk actuators, requiring a limit on the maximum operating frequency to maintain stability. In contrast, layered-structure piezoelectric motors can operate in auto-frequency mode because self-heating produces much smaller eigenfrequency shifts.

References

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