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Feedback control of thin film PZT MEMS actuator with integrated buried piezoresistors

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ABSTRACT

In this paper, a thin film PZT MEMS actuator feedback controlled with integrated buried piezoresistors is reported. Two PID controllers were used to implement a phase-locked loop (PLL) with automatic gain control (AGC). The amplitude of the device could be precisely controlled by using the buried piezoresistors. The proposed fabrication process was compatible with both components. The positioning accuracy and drift as small as 5 ppm and 95 ppb/min, respectively, could be obtained by the proposed system. In addition, the bias stability and the white noise were reduced by 90%.

The results presented here show significant improvement of the precision and stability of the PZT-based device.

1. Introduction

Piezoelectric transduction has experienced increasing popularity for MEMS actuators because of its low power consumption, large actuation force and small footprint in comparison to the other transducers such as electrostatic, electromagnetic, or electrothermal ones [1]. Lead Titanate Zirconate (PZT) thin film is one of the piezoelectric materials with largest piezoelectric coefficients [2], thus it is widely used in a vast variety of MEMS sensors and actuators such as inkjet printheads [3], pMUTs [4], inertial sensors [5,6], energy harvesters [7,8], acoustic transducers [9] and optical devices [10–12].

The emerging applications are often subjected to much harsher environment conditions such as working in air, which exposes them to humidity and dust, and operation regimen is more demanding, with large displacements desired and non-resonant actuation required. Because of this, the long-term stability problems of thin film PZT become challenging in newer applications.

Thin film PZT has been reported to exhibit long-term electrical fatigue [13,14]. Mazzalai et al. [15] claims that the performance damage can be recovered by temporary actuation suspension, suggesting that the phenomenon leading to fatigue may be heat related. Even if the damage is not permanent, it certainly affects the long-term performance and reliability. In addition, temperature-dependent aging affecting the film's piezoelectric coefficients during the first several hours after poling has also been reported [16]. These instabilities degrade the accuracy of the PZT actuator.

Although significant improvement to the PZT's reliability have been done [17], perfectly eliminating long-term instabilities is difficult. Thus, we propose to compensate for them by applying a feedback control system with an integrated position sensor. There are many examples of MEMS actuators with control systems [18,19] and several with built-in sensors [20–24]. In the case of piezoelectric MEMS actuators, piezoelectric sensing using the same thin film is preferred [25–27] and a natural choice. But thin film PZT sensors are also subjected to the same defects, and its non-linear behavior due to hysteresis complicates the control system. In addition, some applications may need or benefit from quasi-static actuation, which cannot be measured by the piezoelectric sensors.

On the other hand, silicon piezoresistive sensors can measure the static deflection and are known for their high precision. Therefore, they are promising candidates for position control of PZT actuated devices. Indeed, a recently developed micromirror with PZT actuation and piezoresistive sensing [28] has shown impressive long-term stability. This validates the interest on the PZT-piezoresistor combination for position control.

One of the problems that may arise with the piezoresistor is output fluctuation due to the surface condition. Esashi et al. [29] reported the sensitivity highly fluctuated when exposed to humidity. Also, Kim et al. [30] reported that the combination of solgel PZT thin film and silicon piezoresistive sensors was affected by electrical coupling. Therefore, the piezoresistor is usually covered by

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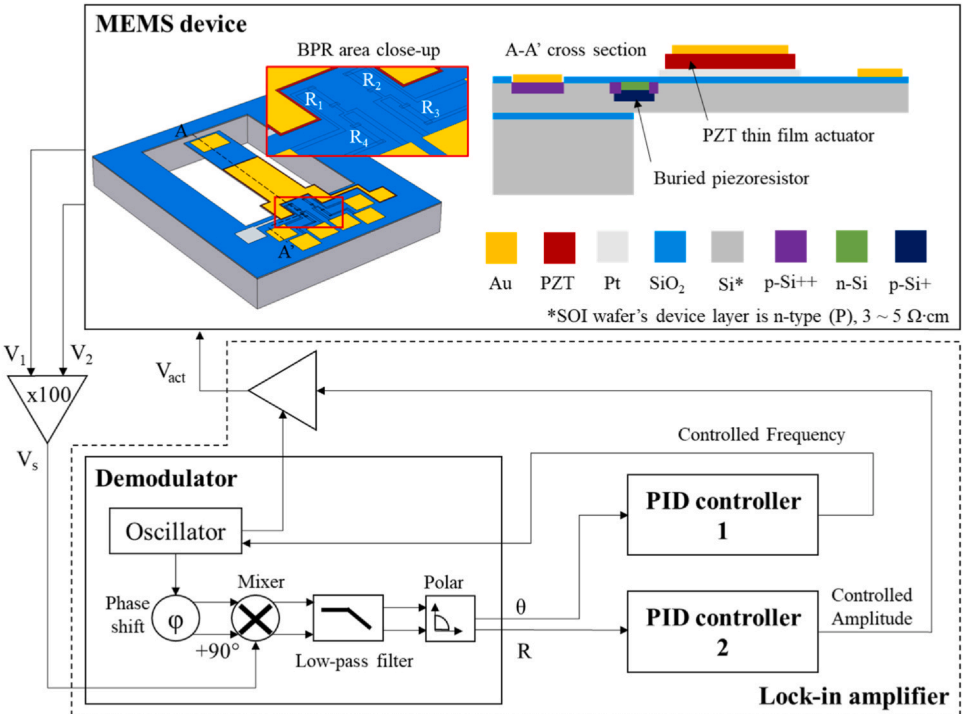

Fig. 1. Block diagram of device-controller system.

Table 1
Summary of device characteristics.

Property	Magnitude
Cantilever length	1500 µm
Cantilever width	400 µm
PZT thickness	1 µm
Resonance frequency	6300 Hz
B concentration (resistor)	~10^{18} /cm^3
P concentration (resistor cover)	10^{21} /cm^3
Sensing circuit bias voltage	1 V
Buried piezoresistor sensitivity	0.037 mV/µm
Sensing noise density	1×10^{-6} V/√Hz
Temperature coefficient	0.24%/°C

passivation layer made of SiO_2 or SiN_x. However, this protective layer would become the buffer layer of the PZT, thus it must be compatible with the PZT deposition process. In terms of PZT film quality, thermal SiO_2 is preferable, which cannot be grown after the piezoresistor formation. Therefore, the thickness of SiO_2 must be less than a few tens of nanometers for the ion implantation. To solve the stability problem, buried piezoresistors [29] were employed, in which the active layer of piezoresistor is buried about 1 µm from the surface and covered with n-type Si. The detailed fabrication was already reported [31].

In this paper we report on the feedback control of the piezoelectric MEMS actuator with the buried piezoresistive sensors.

2. Control system design

In this paper, we demonstrate the feasibility of the feedback system as the phase-locked loop (PLL) with automatic gain control (AGC). Fig. 1 shows the block diagram of the device with the feedback control. The device used in the system was the MEMS cantilever with thin film PZT actuator and four buried piezoresistive sensors. It was fabricated on a SOI wafer, of which the device layer was n-type and resistance of 3–5 Ω·cm. First, the buried piezoresistors were fabricated by three steps of implantation and then, the PZT actuator was fabricated by solgel deposition (1 µm thickness). The detailed fabrication process was reported in the previous paper [31].

Two piezoresistors, R_1 and R_2, were placed at the root of the cantilever and change their electrical resistance when the cantilever deflects. Other two piezoresistors, R_3 and R_4, were placed away from the cantilever to be used as the reference resistors. The four piezoresistors form a Wheatstone bridge, of which the output can be written as

$$V_2 - V_1 = \left(\frac{0.5 \quad (\pi_{11} + \pi_{12} + \pi_{44})\sigma}{2 + 0.5(\pi_{11} + \pi_{12} + \pi_{44})\sigma}\right)V_{bias}, \tag{1}$$

where π_{ij}, σ and V_{bias} are the piezoresistive coefficients, applied stress and bias voltage to the bridge circuit, respectively. The sensitivity of the device was estimated to be about 0.037 mV/µm. The device characteristics are shown in Table 1.

This output was amplified with a gain of 100 by an instrumentation amplifier (AD624, Analog Devices Inc.). The amplified detection signal, V_s, was demodulated by the actuation signal to detect the phase, θ, and amplitude, R. Two PID controllers were used to control both the phase and the amplitude, which are called as PLL and AGC, respectively. The demodulator and PID controllers were implemented in a lock-in amplifier (UHFLI, Zurich Instruments, Switzerland).

The actuation signal to the PZT actuator was within 1.5 V_{pp}, due to the limitation of the equipment. The PZT was driven in bipolar mode, *i.e.*, DC offset of the actuation signal was 0 V.

Since the device was to be operated constantly at resonance frequency (6.3 kHz), it can be modeled as a simple first order system by the following expression

$$G(s) = \frac{K}{\frac{2Q}{\omega}s + 1} \quad , \tag{2}$$

where K, Q and ω are the steady state output, the device's Q-factor (174) and angular frequency (about 39,584 rad/s), respectively. Fig. 2 shows the time-domain response of the sensing signal's demodulated amplitude when a sine wave of 1 V_{pp} was applied to the

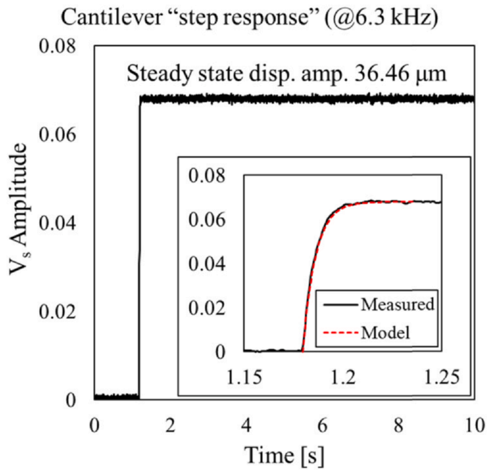

Fig. 2. Sensing signal demodulated amplitude time response to 1 Vpp sine wave at 6300 Hz. First order system model step response is shown in inset, showing a good fit to the transient response of the device. The corresponding steady state amplitude in displacement measured by LDV was 36.46 μm.

actuator at resonance frequency. The steady state output K was extracted from this data, which was about 0.066. The first order model was a good fit, as shown in the inset of Fig. 2.

The controller for ACG was designed by root locus method. The transfer function of the selected controller was

$$C(s) = \frac{50s + 500}{s} \quad , \tag{3}$$

which means a PI controller with $P = 50$ and $I = 500$. From the Bode diagram, the phase margin was found to be 121° at 164 rad/s, confirming the system stability.

3. Evaluation

The fabricated device was evaluated using the system shown in Fig. 1, without control or acquisition of the environmental conditions. However, the PID controller for the ACG used different parameters (P: 250, I: 18, D: 1.3), which were adjusted manually for the tests. The PLL worked correctly at the resonant frequency. Fig. 3 shows the measured amplitude of the device.

The red line in Fig. 3a was the target value of the AGC. As can be seen, the oscillation amplitude well followed the target value. Since the maximum voltage applied to the actuator was limited to less than 1.5 V, the gain of PID controller is also limited at a small value. To reduce the settling time observed, a couple of alternatives are discussed later.

The relationship between target and measured amplitudes is shown in Fig. 3b. The oscillation amplitude was linearly proportional to the target value. In the figure, average of the residual error as well as standard deviation of the measured amplitude are also shown. The average error and standard deviation were about 0.2 mV and 0.19 mV at the steady state, respectively.

The comparison of the device output with and without feedback control is shown in Fig. 4. The data was recorded at the steady state. Without feedback control, the oscillation amplitude was manually controlled by the actuation voltage. Fig. 4a and b compare the short-term performance and stability over 28 min, respectively.

The residual error without control was 22.9 μV, while that with control was 0.1 μV, which means the residual error was only 5 ppm of the target value. The standard deviation was reduced by 43%.

In the stability experiment (Fig. 4b), when the feedback control was not applied, the amplitude slightly drifted with the slope of about −2.6 μV/min. On the other hand, almost no amplitude drift, as small as 80 nV/min, could be observed with the feedback control.

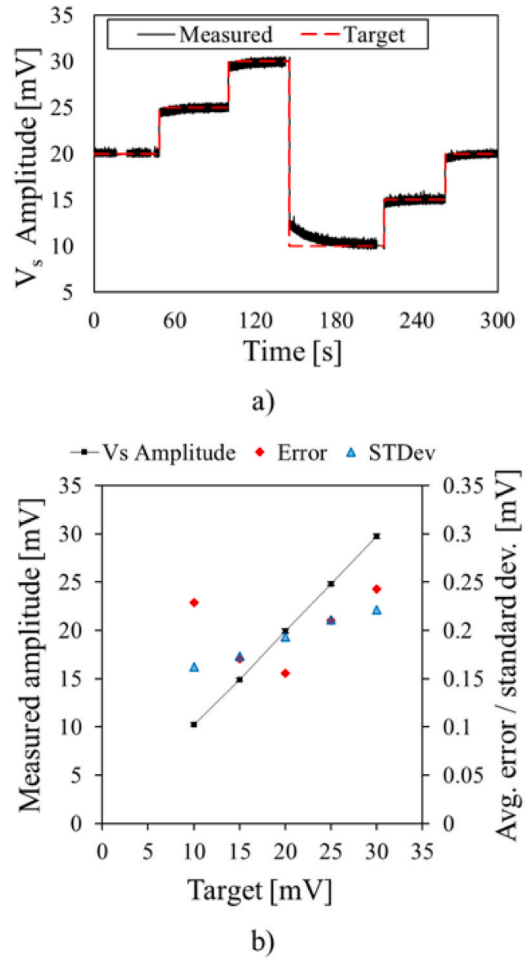

Fig. 3. Automatic gain control. a) Response to changing setpoints. b) Relationship between sensing signal, residual error, and standard deviation at different setpoints.

Fig. 5 shows the Allan deviation of the sensing signal amplitude with and without feedback control. The environmental conditions, such as temperature, humidity, and pressure, were not controlled during the measurement. The bias stability as well as white noise could be reduced to be about 1/10 with the control.

4. Discussion

The positioning accuracy of the PZT micro actuator was improved significantly by the feedback control using the integrated position sensor. For high precision, the buried piezoresistor was selected. The fabricated device was actuated by the PZT thin film and the position was detected by the integrated buried piezoresistors [31].

The feedback system could control the amplitude of the device as shown in Fig. 3. The overall residual error was about 0.2 mV in steady state, or in the order of 1% of the setpoint. However, long settling times of several seconds (and over 30 s for the step from 30 to 10 mV), were observed. Increasing the gain of the controller should solve this problem.

Due to the limited driving voltage, increasing the controller gain is also limited. In addition, the large high frequency noise observed in the Allan deviation (Fig. 5) becomes higher with larger controller gain. However, if a low pass filter is used, simulation shows that the response speed can be improved by choosing larger proportional and/or integral terms, as shown in Fig. 6. Another alternative is to use an amplifier for the controller output. During the previous study [31], up to 10 V_{pp} was applied to the device without showing signs of

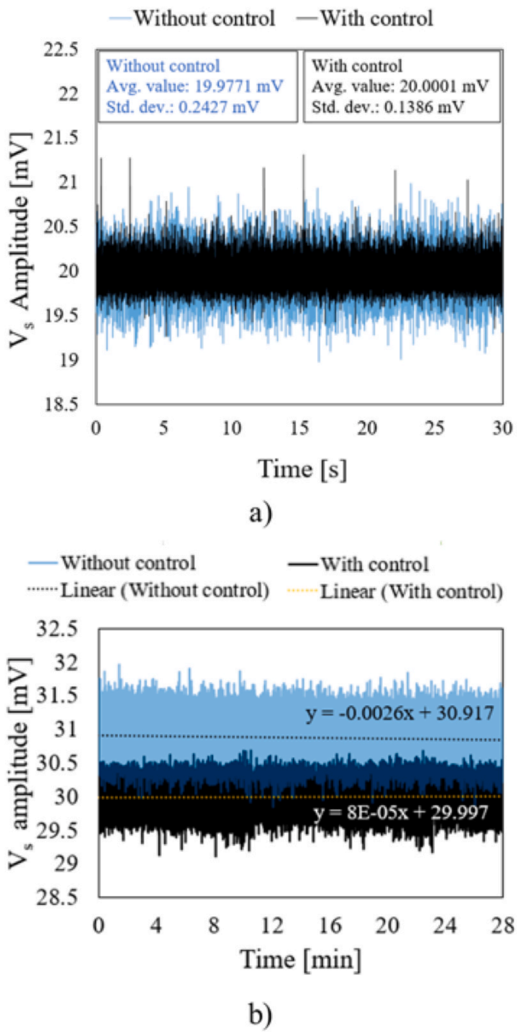

Fig. 4. Comparison at the steady state without control (light blue) and with control (black). a) Short-term (30 s) measurement. b) Stability measurement (28 min).

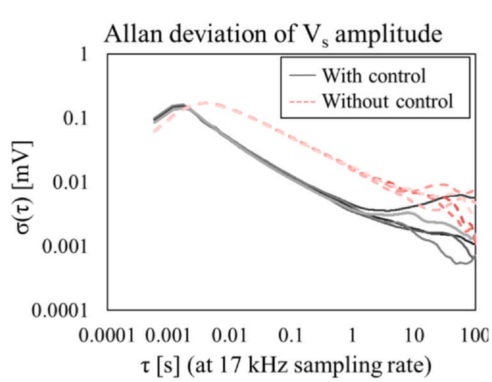

Fig. 5. Allan deviation of sensing signal amplitude with and without control (5 segments of 5 min in each case).

saturation. Therefore, there is a significant margin for speeding up the response through amplification of the actuation signal.

In the short-term, the control reduced the residual error to as low as 5 ppm of the target value.

Regarding the stability, thin film PZT is known to exhibit electrical fatigue over time, but 28 min at 6.3 kHz was too short for this phenomenon to explain the drift, especially at low actuation voltage (less than 1.5 V). Therefore, the drift shown in Fig. 4b might had come from the Q-factor and resonant frequency fluctuation caused by the temperature change. The total drift without control was about 0.0728 mV after the 28-minute run, which corresponds to 19.46 nm in displacement according to the device's sensitivity [31]. If the temperature coefficient of frequency (TCF) is assumed to be −30 ppm/K, this fluctuation corresponds to a temperature fluctuation of 0.9 K. The temperature of the experimental setup was not controlled, so the estimated temperature fluctuation is reasonable. However, when applying the feedback control, this fluctuation could be successfully compensated. The amplitude drift with the control was 2.24 μV. From the sensitivity of the position sensor, the displacement drift was 599 pm, which corresponds to the equivalent temperature fluctuation of only 28.3 mK. This is a rough analysis and no actual temperature sweeps were performed. Real behavior under temperature sweeps will be studied in future works.

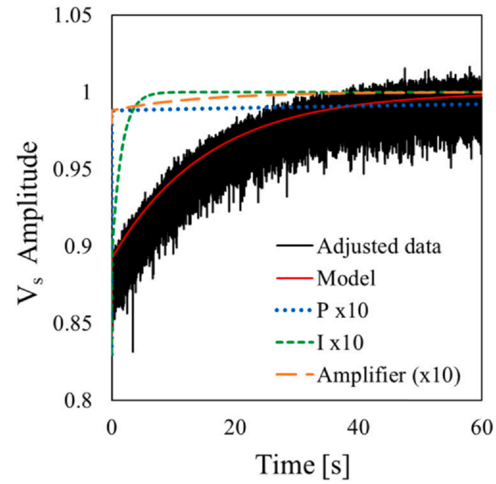

Fig. 6. Alternatives for faster response. The experimental data (black) agrees well with simulation (red). Increasing the proportional (blue) or integral (green) gain or using an external amplifier (orange) result in speed improvement without compromising stability.

The presented results show that the performance of a PZT-based MEMS actuator can be significantly improved by using piezoresistive sensing. The micromirror developed by Frigerio et al. [28] also showed piezoresistive sensing was suitable to control PZT actuators. Their PZT thin film was deposited by sol-gel method too, but the piezoresistors were reportedly made of n-type Si, instead of p-type buried piezoresistors which could increase the stability of the sensor even in a not-well-controlled environment [29]. Their approach was similar to the presented in this paper, with the control circuit basically consisting in a phase loop and an amplitude control loop. One difference is that we used lock-in detection and demodulation technique to extract the amplitude, while they rectified, filtered, and amplified (i.e., AM-demodulation) the piezoresistors' output to obtain the sensing signal amplitude.

From the fabrication point of view, the PZT/piezoresistor combination has had some compatibility issues in the past, with conventional piezoresistors not suitable for integration with PZT thin film because the standard insulation layer, SiN_x and chemical vapor deposition (CVD) SiO_2, does not provide a viable buffer layer for the PZT deposition. This problem was solved by using buried piezoresistors instead, which can be insulated with a very thin thermal SiO_2 of just 40 nm and allow for PZT thin film deposition.

5. Conclusion

The feedback control of a piezoelectric MEMS actuator with integrated buried piezoresistors was proposed and demonstrated. The amplitude of the device could be precisely controlled. The position inaccuracy was as small as 5 ppm with the feedback control. In addition, the amplitude drift could be compensated to be less than 100 ppb/min.

These results are promising for the substantial improvement of the long-term stability and the achievement of reliable position control in thin film PZT-based actuators.

CRediT authorship contribution statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Journal of Sensors and Actuators Physical A.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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