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Thermal effect on piezoelectric stick-slip actuator systems

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The piezoelectric stick-slip (PZT-SS) actuator is known to achieve motion with a theoretically unlimited range yet high resolution (several nanometers). In this type of actuator, friction plays an active role in producing a meaningful stick-slip motion. However, friction is a source of heat which may cause significant temperature rise, affecting the dynamic performance of the actuator. Our study aimed to measure temperature rise in the stick-slip motion and to understand whether such a rise could significantly affect the displacement of the stick-slip motion. In this study, a temperature measurement system was developed using the off-the-shelf components, with which the temperature rise up to 0.436 °C was successfully measured on a proprietary PZT-SS actuator. The experiment further shows that the temperature rise affects the displacement of the actuator when operating voltage is at the low end (~6 V). Therefore, one of the design recommendations for such an actuator system is that the operating voltage should be at the high end (~30 V). The study also measured the temperature rise (~0.263 °C after the system worked for 6300 s) at the friction interface due to the piezoelectric element which is a part of the whole PZT-SS actuator. This means that temperature rise is due to both the friction at two interacting surface and the operation of the piezoelectric element. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2908162]

Actuators are desired to have a long motion range with high resolution.[1] The piezoelectric (PZT) actuator is known for its high resolution and fast response compared to other direct actuators which are based on effects such as electromagnetic, shape memory, and magnetostrictive.[2,3] However, the motion range of the PZT actuator is typically too small (less than 1 mm). Both the advantage and disadvantage of the PZT actuator come from an inherent property of the PZT element—that is, the PZT element can deform up to 0.1%–0.15% of its thickness (several nanometers) of the piezoelectric element under an electrical voltage applied along its thickness direction; further, this deformation can be taken with high frequency (e.g., thousands of hertz).[4] The stick-slip (SS) actuator enjoys its long motion range with a relatively low resolution (at microns level).[5] Combination of the PZT and SS actuators into a new actuator called PZT-SS is, thus, an excellent idea.[6]

Breguet and Clavel *et al.*[4] described a one-degree-of-freedom (1-DOF) PZT-SS actuator which achieves the motion range up to several centimeters and the resolution of less than 5 nm. Hack[7] proposed a PZT-SS rotary actuator with its angular resolution as small as 0.2 arc sec and a rotation range of 2π or more. Polla *et al.*[8] designed a PZT-SS linear actuator for precision surgical applications. Their actuator can achieve total displacements of 38 mm. Zhang *et al.*[5] developed a 2-DOF PZT-SS rotary linear actuator. Their experiment has further shown that the actuator can achieve an unlimited motion range with the linear resolution of 26 nm and angular resolution of 0.019°.

Though the dynamic performance of the PZT-SS actuator has been extensively studied in the literature, heat generation in and its effect on this type of actuator have not. In the PZT-SS actuator, because friction plays an active role and accuracy in motion is desired to be very high, the friction-induced heat may perhaps have a significant thermal effect on the dynamic performance of the actuator. Our study aimed to measure temperature rise in the slip-stick motion and to understand whether such a rise could significantly affect the displacement of the SS motion. In the remainder of this paper, Sec. II presents our measurement system, and in Sec. III, the measurement result along with discussions is presented.

The mechanical system of a PZT-SS actuator prototype for the temperature rise measurement system is shown in Fig. 1. This system is composed of a piezoelectric element, frames, a stage, a wheel, several weights, an end effector, and two friction plates. The piezoelectric element is glued to the frame at one end and the other end is firmly connected with the stage. The two friction plates between the end effector and the stage are to regulate the friction force—particularly by changing plates with different materials and surface qualities. The weights are to adjust the pressure between the end effector and stage to change the friction force as well. The wheel is to support the stage. The whole system was put on a vibration isolation table which significantly isolated vibration disturbances to the system.

The control system for the PZT-SS actuator was de-

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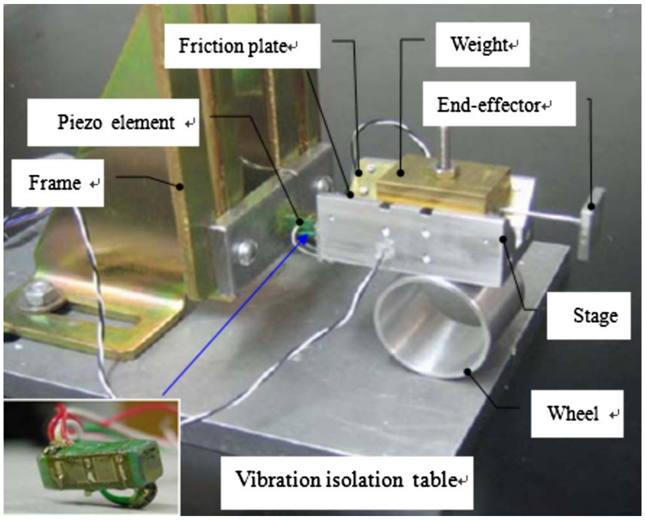

FIG. 1. (Color online) Prototype of the PZT-SS actuator.

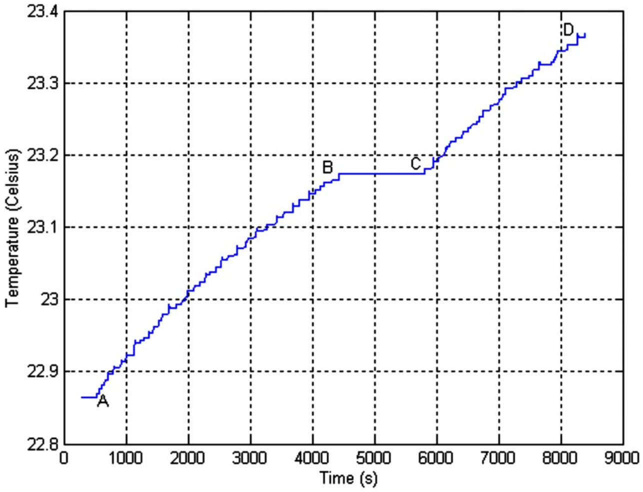

FIG. 3. (Color online) Temperature rise at the friction interface in the PZT-SS actuator.

signed as an open-loop system and implemented with DSPACE and MATLAB/SIMULINK. Temperature rise may significantly come only after a certain period of time. This requires that the actuator system performs a reciprocating motion which was realized with two modes of the voltage input. The switch between two modes was automatically managed in the control system.

The measurement of temperature rise on the friction interface and measurement of the displacement at the end effector were designed. Thermal sensors were designed and placed underneath the friction plate (Fig. 2). The thickness of the plate was made as small as possible, and its material was with as large thermal conductivity as possible. In particular, (1) the platinum resistance sensor (model: HEL-705-T-0-12-00, Manufacturer: Honeywell) was employed, (2) the thickness of the friction plate was 0.003 in., and (3) the material of the friction plate was brass. Further, the displacement measurement was taken by KAMAN instrument (model: SMU 9000-15N-001 3 CH) which is based on the eddy-current inductor principle.

Based on trial-and-error tests, a low-pass Butterworth filter with the cutoff frequency of 0.5 Hz and the order of 10 was designed for eliminating the noises. The compensation for the offset and attenuation of the filter were also considered to improve the measurement accuracy further. To eliminate as many as external disturbances to the measurement system, the measurement was conducted under the following conditions: (A) the whole system was put in a heat-insulated chamber which was located in a room with temperature between 23.5 and 24.5 °C, and (B) the whole system was put on a vibration isolated table.

Figure 3 shows the result of temperature rise which was obtained by us. The curve segments A-B and C-D, respectively, correspond that the system was in operation and there was temperature rise. The curve segment B-C corresponds that the system was stopped and temperature kept constant because the whole actuator and measurement system were put in the heat-insulated chamber. Furthermore, the slopes of curves A-B and C-D are the same, which suggests that the whole measurement system be of excellent repeatability.

During the measurement, it was found that the piezoelectric element also generated significant heat causing temperature rise at the friction interface. Figure 4 shows temperature rise due to the heat generated from the piezoelectric element movement; in particular, curve A corresponds to the

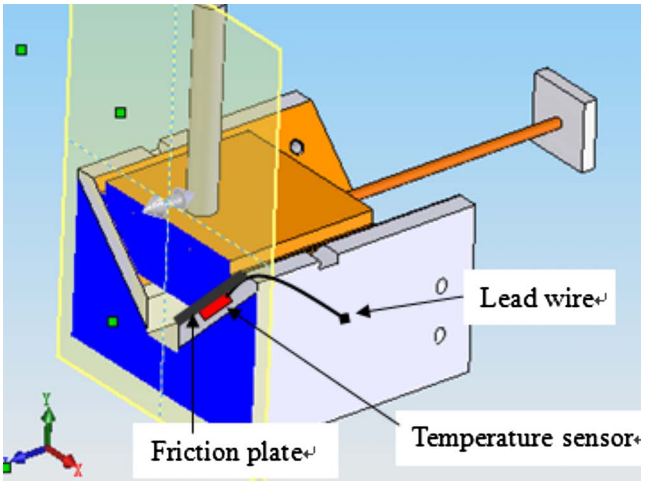

FIG. 2. (Color online) Location and placement of the thermal sensor.

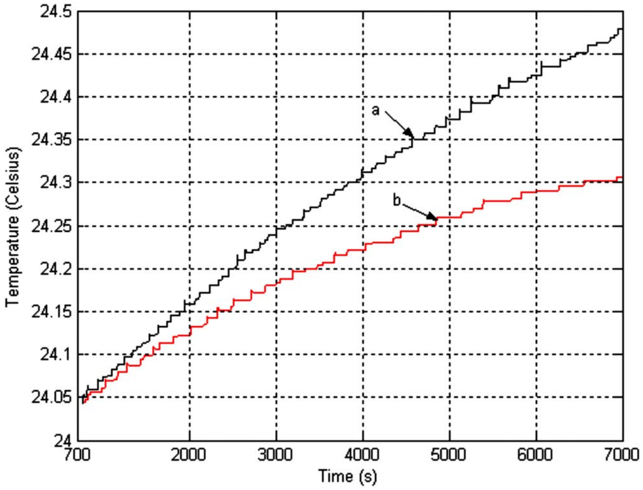

FIG. 4. (Color online) Temperature change in the actuator system under different situations.

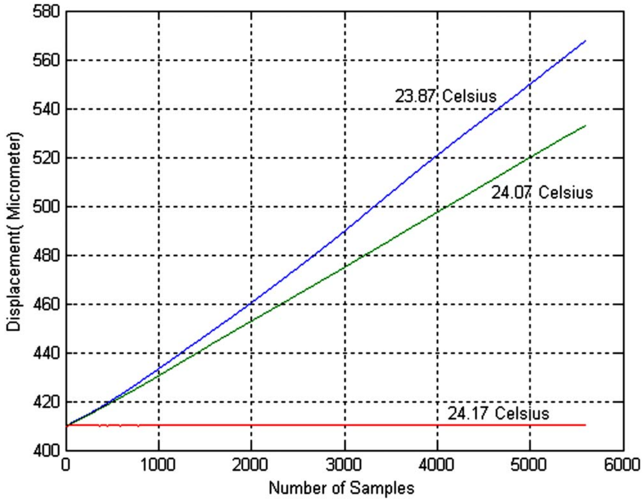

FIG. 5. (Color online) Effect of temperature rise on the displacement performance of the PZT-SS actuator (input voltage is 6 V).

situation where the whole system is in a full operation and curve B to the situation where only the piezoelectric element is in operation. For both situations, the location of temperature is at the friction interface. From Fig. 4, it can be found that the temperature rise (0.263 °C) caused due to the piezoelectric element tends to reach a stable state—the rate of the temperature rise significantly decreases after the actuator runs 7000 s, while the temperature rise due to the friction at the interface between the stage and end effector tends to take a much longer time to reach a stable state. The total amounts of temperature rises in the PZT-SS actuator are about 0.436 °C after the actuator runs 6300 s

Figure 5 shows the displacement of the actuator under different temperatures where the input voltage is 6 V (low end of voltage called hereafter). It is interesting to find from Fig. 5 that when temperature rise is up to 24.07 °C, the displacement significantly changes. However, after temperature rise is up to or larger than 24.17 °C, the produced displacement is extremely small. This may be because when temperature rise is higher, the material tends to have more deformation. More deformation at the friction interface between the stage and end effector could lead to more friction on the interface; as such the displacement may be blocked.

Figure 6 shows the effect of temperature rise on the displacement of the actuator when input voltage for the piezoelectric element is 30 V (high end of voltage called hereafter). It is interesting to observe that the effect this time significantly differs from that when the input voltage is 6 V–in particular, the difference in temperature rise when the input voltage is 30 V does not appear to significantly change (the two curves in Fig. 6 are very close). This may be because a large voltage implies a large driving force which sufficiently overcomes the increase of friction due to temperature rise. Therefore, one of the design recommendations for such an actuator system is that the operating voltage should be at the high end.

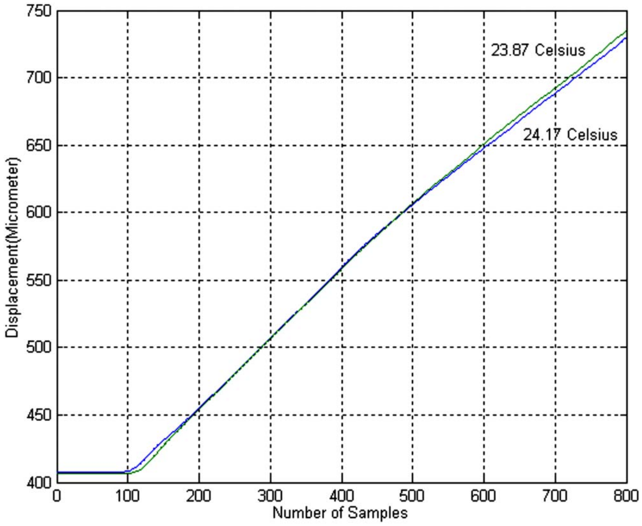

FIG. 6. (Color online) Effect of temperature rise on the displacement performance of the actuator (input voltage is 30 V).

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