Elimination of thermal instability in precise positioning of Galfenol actuators

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ABSTRACT

This paper presents a new method to eliminate deviation in positioning caused by coil's heat generation in magnetostrictive actuators. The advantages of the proposed system are compactness, high controllability and high reliability. The actuator package consists of Galfenol as active element and a magnification mechanism combined with a Peltier element or thermoelectric cooler (TEC). By using the temperature sensor, a thermoelectric cooler (TEC) is activated to reduce the temperature of the coil. However, the reduction of temperature by TEC alone is not enough to eliminate the error and controlling of applied voltage is also required. A simple PI controller for coil's current is combined with TEC and by reducing the temperature and current simultaneously, the positioning error is vanished completely.

Keywords: Galfenol, Precise positioning, Thermal instability, Peltier element (TEC)

1. INTRODUCTION

In last decay, high speed response smart materials like magnetostrictive, piezoelectric and magnetorheological materials play significant roles in mechatronics systems. Terfenol-D [1-4], Galfenol [5-6] and Permandure [7-8] are widely used as actuation elements in the new generations of actuators [9-11] while these materials are widely used in sensors [12, 13] and energy saving systems too [14]. Piezoelectric elements like Lead Zirconate Titanate (PZT) have also today numerous applications in electro-mechanical systems such as actuators for medical applications [15-16], health monitoring transducers [17-19]. Magnetorheological materials also are suitable for flexible and tactile actuators, however, low speed response can be counted as their drawback [20-21].

Among these materials, piezoelectric and magnetostricitve (MS) are wieldy used in actuators for precise positioning. Since strains of piezoelectric and magnetostrictive materials are small compared to the shape memory alloys and electro active polymers and magnetorholocical, different magnifying mechanisms were presented [5, 8, 16]. For examples micro amplification mechanism with sub-nanometer resolution in microelectronics industries were developed by micro positioning stages using lever mechanism and piezoelectric. The magnification ration of some of these mechanisms is about 60 which a big displacement of 1.6 mm was achieved [16]. Although actuators with piezoelectrics driven element has high frequencies, they are not suitable for cryogenic and high humidity or in the other words, harsh environments. Furthermore, piezoelectric needs high voltage. It was shown that Magnetostrictive materials are good candidates to operate in low temperature and low voltage [5]. However, the problem of magnetostrictive material is the heat generated by coil which increases the temperature. Therefore, to keep the desired position of actuator's tip for a period of time which is called "holding time", the coil should be energized continuously. The position deviation proportional to the

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holding time is detected because of coil's generated heat. In this paper a new practical method for eliminating thermal instability in positioning is presented.

2. PROBLEM STATEMENT

Internal and external disturbances cause positioning error in MS actuators. Hysteresis and eddy current play significant role in positioning error when the actuators are energized by AC power supply. Any obstacle or resistant load against to the head of actuator can be considered as external disturbances. In this research, main concentration is on the internal disturbances and mainly on positioning error results from the coil's heat. As the coil is energized to keep its position for holding time, the induced magnetic field causes strain in MS material. However, as the current pass through the coil, part of electrical energy is converted to the magnetic energy and part of this energy is dissipated to heat because of Ohmic resistance of coil. Therefore, displacement of MS actuator's head is made by strain of both, magnetic field (Eq. 1) and thermal energy (Eq. 2). In other words, positioning error is proportional to the conducted heat to the magnetostrictive rod.

$$\varepsilon_{magnetic} = \frac{\Delta L_{magnetic}}{L} = \frac{2\,B_0 \Delta B}{E\mu}$$

(1)

Where B_0 is the magnetic flux density at working point, ΔB is variable quality of magnetic flux density, μ and E are the magnetic permeability and the Young modules of Galfenol, respectively. If the generated heat by the coil causes change in the rod temperature (ΔT), the thermal strain is calculated by (2).

$$\varepsilon_{thermal} = \frac{\Delta L_{thermal}}{L} = \alpha\,\Delta T$$

(2)

Where α is thermal expansion coefficient of Galfenol. The total strain is obtained by (3) that its second term made by heat is presented as the positioning error which is equal to the $\alpha\Delta T$.

$$\varepsilon_{total} = \varepsilon_{magnetic} + \varepsilon_{thermal} = \frac{2\,B_0 \Delta B}{E\mu_0} + \alpha\,\Delta T \qquad (3)$$

As shown in Fig.1, PZT actuator can keep its position for its holding time. However, the Galfenol actuator shows instable behavior because of coil's heat conducted to the Galfenol. Many cooling systems were proposed to remove the generated coil's heat. For examples, Kwak et al. [22], Witthauer et al. [23] and Wang et al. [24] have proposed different air cooling systems and Quanguo Lu et al. [25] and Zhu et al. [26] proposed water cooling systems. Both, air and water cooling systems are suffering from the high cost, difficult sealing and low efficiency. However, in this research Peltier element which is Thermoelectric Cooler (TEC) is exploded which is high response element, cheap, compact and have no insulation problem.

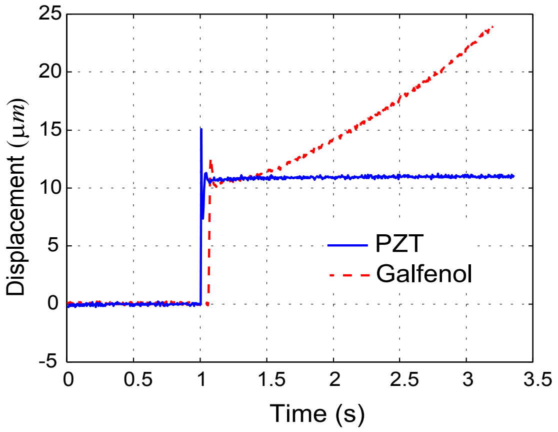
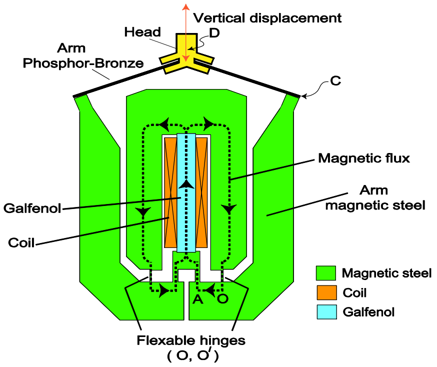


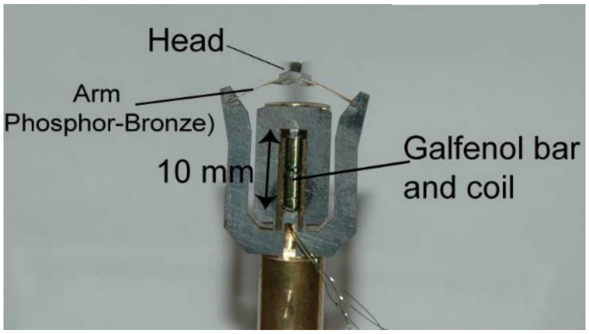
Fig.1: Precise positioning using magnetostrictive and PZT actuator

3. PRINCIPLE OF MAGNETOSTRICTIVE ACTUATOR

Figure 2a shows a schematic configuration of Galfenol actuator. To increase the performance of this actuator, its two main parts make a close magnetic circuit [27-29]. The first part is a Galfenol bar as actuation element and the second part is a magnifying mechanism to amplify strain of the Galfenol. To enhance the performance of magnetic circuit, the magnifying mechanism is made of high permeability magnetic steel [30]. The length of Galfenol bar is 10 mm and its cross section is square by 1 mm thickness (Fig. 1b). The maximum strain of annealed Galfenol is about 250 ppm. Thickness of magnifying system is 0.8 mm and energized coil is φ=0.05 mm, 240 turns. Galfenol displacement is transferred to the head by phosphor-bronze spring plate. By energizing the coil, generated magnetic fluxes pass through the Galfenol bar and increase its length. Similar to lever mechanism this enlargement is magnified almost 6 times and large vertical displacement is achievable by head. The initial evaluation shows that 15 μm vertical displacement is achievable by this miniature actuator.



(a)



(b)

Fig.2: (a) Schematic of magnetostrictive magnifying system (b) real actuator

4. POSITION CONTROL SCHEMES AND COOLING SYSTEM

The closed loop control system is the most appropriate method to reduce the positioning error in actuators. Usually, displacement sensor is exploited as a feedback signal in active control system (Fig. 3). However, to keep the tip of the actuator in a specified position, the coil should be energized by a constant voltage. This constant voltage causes ohmic dissipation and increase temperature of Galfenol. Sometimes, long time positioning increases the coil's temperature to more than 90 °C. In this research a low cost temperature sensor (LM35) is also proposed as a feedback sensor to activate TEC via relay. However, the amount of removed heat by TEC was not enough to cancel the positioning error completely. Consequently, the current passing through the actuator's coil is controlled by a simple PI controller.

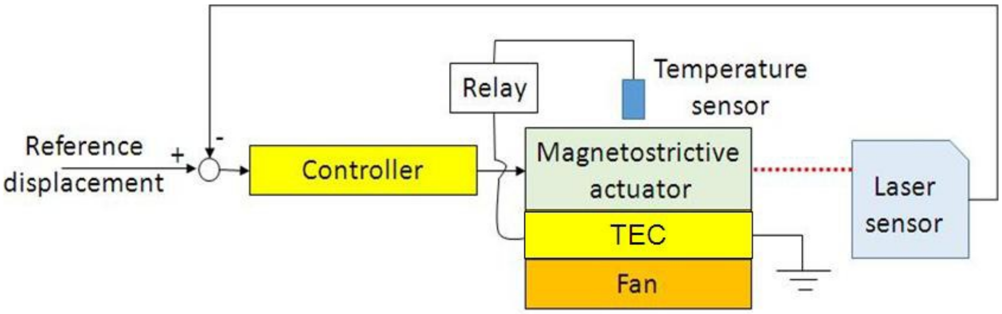
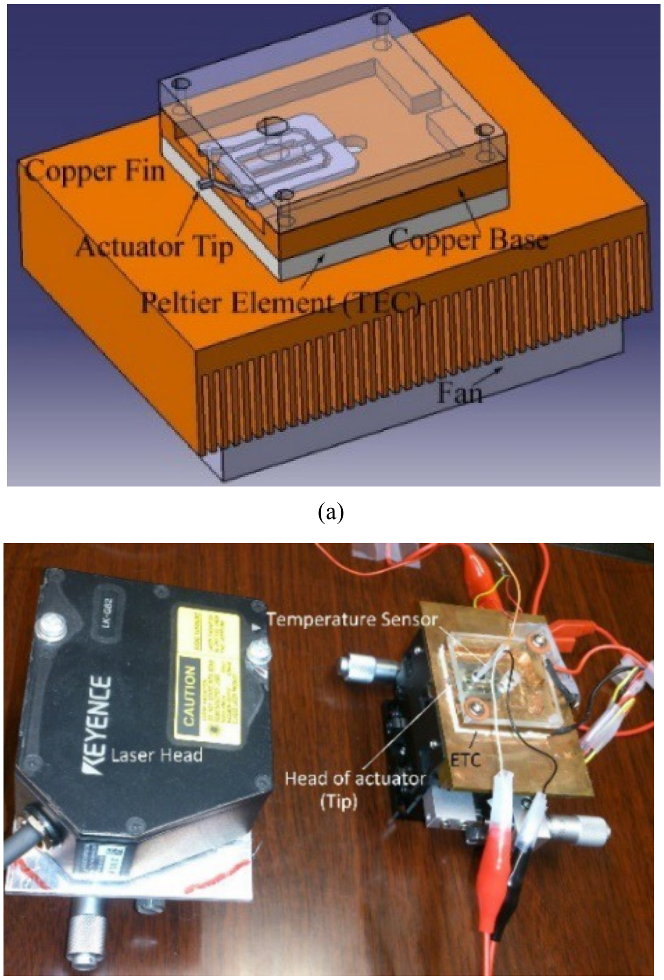


Fig.3: Position closed-loop control block diagram using displacement sensor and TEC.

5. EXPERIMENTAL SETUP

Peltier element or thermoelectric cooler (TEC) is a semiconductor that transfer heat from one side to other side in the opposite direction of temperature gradient (from cold to hot). Usually, this element is used in airplane refrigerator for cooling water. To keep the performance of TEC high, temperature diffidence of two sides of TEC should be controlled. Therefore, a copper fin and a fan are attached to the hot side of Peltier element to remove the heat and keep TEC performance high.



(a)

(b)

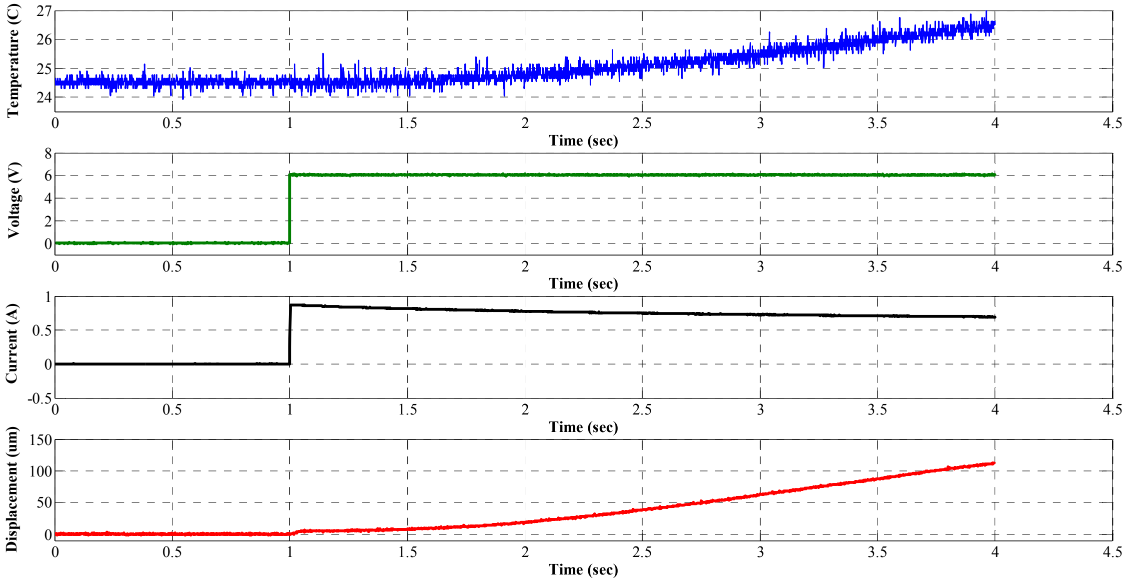
Fig.4: (a) Schematic configuration of magnetostrictive actuator cooled by Peltier element (TEC) (b) Real photo of cooling system

To measure the displacement of actuator's tip, bottom side of actuator is fixed on upper side of a thin copper base (40 mm× 40 mm×5 mm). It is well known, that thermal conductivity of copper is around twice of Aluminum thermal conductivity and is about 400 W/m.k. As shown in Fig. 4, to remove the heat generated by the exciting coil, cold side of thermoelectric cooler (TEC) is bonded with silicon glue to the bottom side of copper base. The heat is removed from the hot side of TEC by a copper fin attached by a high-speed fan. The temperature sensor (LM35) is used to measure coil's temperature. Upper side of actuator is covered by transparent plexy glass which is a good thermal isolator with low thermal conductivity. As it was explained in previous sections, the Galfenol is ductile and EDM is the best way to cut it. The magnifying part is a lever mechanism and its stiffness should be high enough to amplify the small displacement of Galfenol bar with minimum power loss. Moreover, the material should be magnetic material. Therefore, the material is special grade of magnetic steel with high permeability. To manufacture the magnifying mechanism and head, wire EDM technique is exploited which is fast and accurate enough. Keyance laser sensor (LK-G82) is used to measure the displacement on the tip of actuator when it is energized. Our idea for reducing the thermal effect is removing the heat from the magnetostrictive material using Peltier element.

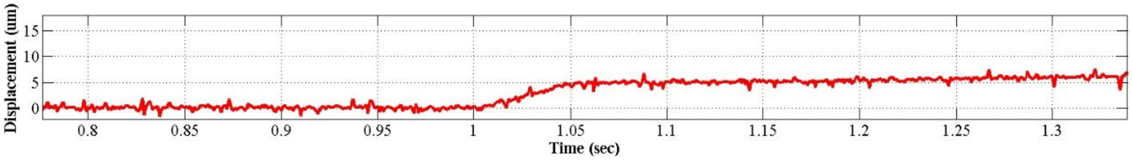
6. RESULTS AND DISCUSION

The relationship between tip displacements of actuator without controlling the coil's current is shown in Fig. 5. By energizing the actuator with step constant voltage, the vertical displacement, coil's temperature, current passing through the coil are measured. As shown in Fig. 5, by applying a 6V constant voltage, a current of 0.8 A is passing through the coil which causes 5 μm displacement in the tip of the actuator. It is found that, by keeping the current for only 3 seconds, the coil's temperature reaches to 27.5 °C from its initial temperature of 24.5 °C. Because of high thermal coefficient of Galfenol (α= 11.7 ppm/°C) a giant error displacement of about 110 μm is produced. Current reduction is predictable because of higher coil's resistor by constant applied voltage. These measurements are repeated by 4V in Fig. 6 and the same behavior is verified.

By using closed-loop control scheme presented in Fig. 4, the thermal disturbance made by coil's heat is eliminated. In this control system, the TEC is switched ON as the temperature is more than 25 °C. Based on the dynamic behavior, resonance frequency of the actuator [5, 31] and model identification [32-35] of actuator, a Proportional-Integral (PI) controller is designed to eliminate the effect of heat. After precise tuning, the coefficients of PI controller by K_p= 3.25 and K_i=40.52 is exploited. As shown in Fig. 7, the coil is energized to position the tip at 5 μm. To keep the position of 5 μm for 2 seconds, the applied voltage is controlled in a way that reduces the current passing through the coil while the TEC is turned ON.



(a)



(b)

Fig.5: (a) Temperature, voltage, current and displacement vs. time by energizing constant voltage of 6V (b) Zoom of displacement

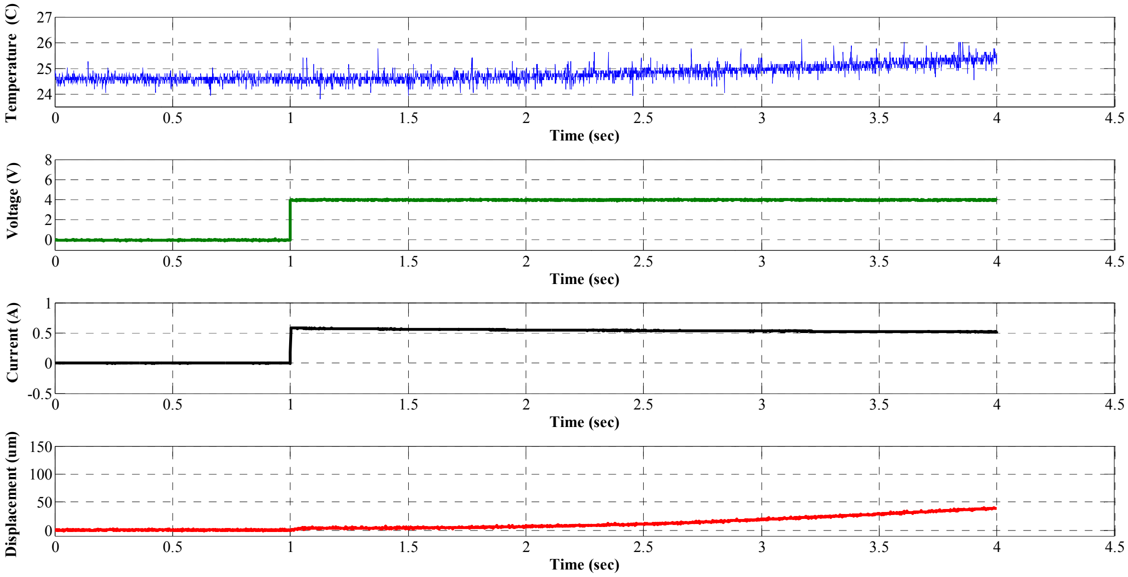


Fig.6: Temperature, Voltage, Current and Displacement vs. time by energizing constant voltage of 4V

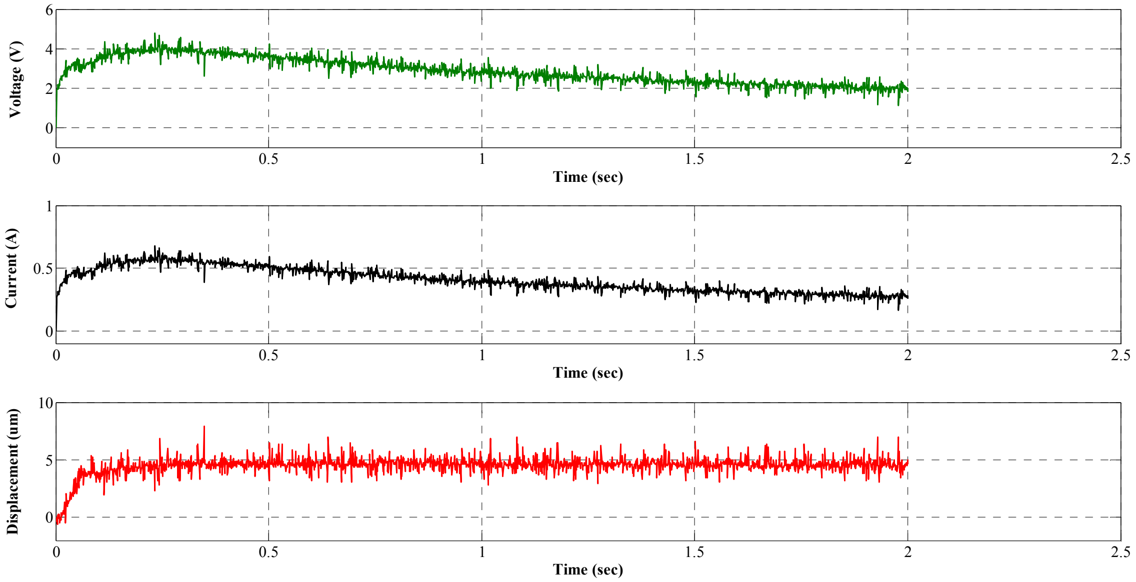


Fig.7: Displacement control using displacement and temperature sensors with turning the TEC

7. CONCLUSIONS

In summary, a closed-loop control technique combined by a cooling system for precise positioning of Galfenol actuator was presented. In this technique, both, displacement and temperature sensors were exploited. It was shown that the temperature rise because of continuous coil energizing is the main reason of positioning error. By using the temperature sensor, a thermoelectric cooler (TEC) was activated to reduce the temperature of the coil. However, the reduction of temperature by TEC alone was not useful and controlling of applied voltage was also required. A simple PI controller was combined to TEC and by reducing the temperature and current, the positioning error was eliminated completely.

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