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Position Control of Shape Memory Alloy Actuator Using A Constant-Resistance Control Method

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Abstract: Since shape memory alloys have functions which sense and respond to temperature, actuators using shape memory alloys do not require temperature sensing devices, electronic processors or electric motors. Therefore, the control systems, which employ shape memory actuators, can be designed compactly and at the same time operation of the control device can be improved. Although the shape memory actuators have been investigated by many researchers, there are few reports that investigate the position control of shape memory actuators. In this work, performance of the position control using a constant-resistance control method is investigated. The produced actuator with rotation mechanism is heated by electric current and it can control the rotational angle at an arbitrary position. The Ti-Ni-Cu alloy wire, which has a relatively small transformation temperature hysteresis, is used as an actuator element. Electric resistance of the alloy is obtained by experiments in relation to the test temperatures.

Key words : actuator, position control, resistance feedback, shape memory alloy, Ti-Ni-Cu alloy

1. INTRODUCTION

The actuators such as AC or DC servomotors enable control of accurate and quick positioning using position feedback system with such position sensors as encoders or resolvers. On the other hand, the actuators using shape memory alloy (SMA) can work as an actuator to control or retain positioning without using sensor device [1,2], because SMA is such a superior element that the element itself has a sensing function in it. This type of sensor-less system brings about many merits like simplification of the system and easy and simple operability. SMA has a characteristic that electric resistance varies due to the phase transformation in the process of heating and cooling, which occurs as a conversion of strain and force. The actuators, applying this characteristic to position control of SMA with resistance feedback, have been reported [3].

However, the resistance values of SMA show non-linear characteristics with hysteresis, resulting in giving different position information for rising and lowering processes of temperature. This means that the real-time resistance values can not be fed back, as is, for the positioning information. Some attempts have been carried out to realize a position control system using the PID control by resistance feedback [4-8], but they remain only at the continuous positioning control or power control. Thus, most applications are limited for the back and forth movement between two given points (not the intermediate points in between). If positioning can be achieved for an arbitrary position, the applications of such actuators will be wide spread.

In this work, a position control system using resistance feedback of SMA is produced and evaluated. Investigation is made on such control characteristics as position accuracy and response time. Furthermore, the effect of OFF time (cooling time) on stability of position control, in the control cycles of heating process (electricity conduction) and cooling process (electricity off-conduction), is investigated.

2. POSITION CONTROL SYSTEM

2.1 SMA actuator

The SMA element used for the actuator is Ti-Ni-Cu alloy, which has a relatively small transformation temperature hysteresis [9]. The alloy wire, which is memory processed in a linear shape, has a length of 400mm and a diameter of 0.15mm. The electric resistance of the alloy is obtained by heating-cooling tests, where Nitrogen gas and the vapor of liquid Nitrogen are used for heating and cooling.

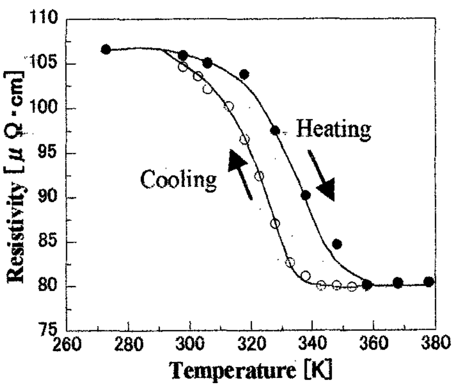

Fig.1 A hysteresis loop of SMA actuator.

Figure 1 shows the variations of electric resistance of SMA with temperature. The resistance of Ti-Ni-Cu alloy wire decreases with increasing temperature and shows a transformation temperature hysteresis of around 14K. The transformation temperatures obtained from the resistance-temperature characteristics are Af=350K, As=312K, Ms=336K and Mf=290K.

2.2 Position control system of SMA actuator

Fig. 2 shows the schematic drawing of a position control system in which an arbitrary positioning can be achieved. The system is composed of pulleys, a bias spring, and a controller circuit so that a linear deformation of the SMA wire can be converted to a rotation angle. In order to compare the performance of position control of actuators with and without a position sensor, wire-wound potentiometer is linked to the rotation axis. Positioning data for the resistance feedback system are obtained from this potentiometer. The SMA wire with an overall length of 400mm is wound 2.5 rounds around the pulley mechanism (6 chains of $\phi 2.5$ pulleys each with 3 tiers), thus enabling linear deformation of SMA to be observed as rotation angle. The controller is so arranged that the cases of resistance feedback and position sensor feedback can be selected with a switch.

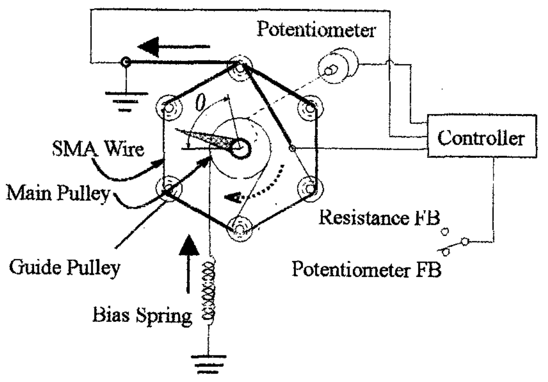

Fig.2 Schematic drawing of position control system.

2.3 Block diagram of position control system

Fig. 3 and Fig.4 show block diagrams of the feedback control system with a potentiometer feedback and with a resistance feedback, respectively. In the potentiometer feedback system (see Fig.3), the voltage variation of the potentiometer and the preset input voltage are fed into a differential amplifier as the input, thus the potentiometer as a position sensor enables a servo loop with a simple circuitry.

On the other hand in the resistance feedback system, the actuator is driven by PID control using variation of the measured resistance values of SMA, not using a sensor. Although the P (proportional gain) in PID is necessary because it relates to heating rate of SMA, the I (integral) simply delays response time of SMA. In addition, though the D (differential) in PID is essential for the instantaneous fluctuation, the feedback differentiated from the irreversibility of SMA is not effective because it is only one way.

Since SMA is a non-linear and non-reversible element with hysteresis characteristics, it can generate a shape recoverable strain through conduction heating but this strain can not be brought back to the non-strain position with conduction of electricity. Therefore, in order to position-control the SMA, electricity needs to be conducted till the resistance value of SMA reaches a preset value and then be put off so that position does not over-pass the desired position. The important point for the accurate positioning is how to control the repetition of "on" time (heating process) and "off" time (cooling process). As shown in Fig.1, the SMA shows non-linear hysteresis characteristics, lowering its resistance value with increasing temperature (i.e. negative resistance characteristics). Taking this into account, conduction-off time is controlled, in the process of resistance lowering, with three different regions of the resistance values R1, R2, and R3 as shown in Fig.5.

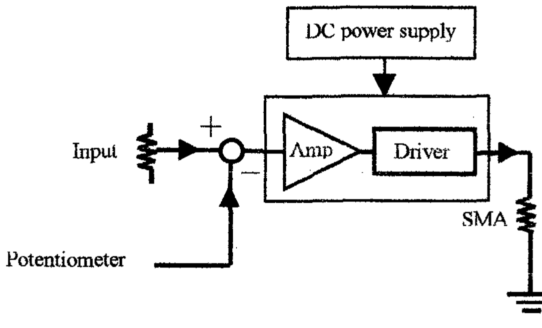

Fig.3 Block diagram with a potentiometer feedback.

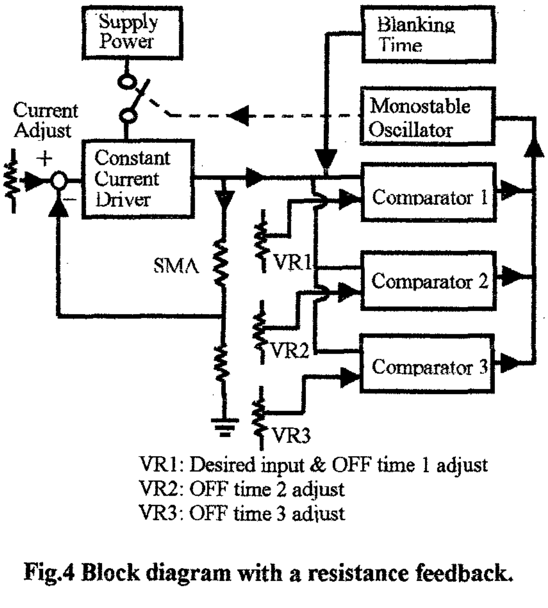

Fig.4 Block diagram with a resistance feedback.

The three comparator circuits shown in Fig.4 selectively switch these R1, R2, and R3 regions, and since resistance characteristics show negative resistance, it is so arranged that the comparators do not detect the resistance values at the time of conduction starting (i.e. blanking time for 15msec). Driver is a constant current type to detect the real-time resistance. In Fig.5, depending on the region (R1, R2, or R3) where the position input (i.e. resistance value) is, the constant resistance feedback is achieved by switching the OFF time through the cycle of, "end of off-time", "conduction on", "detection by comparator" and "conduction off". The times shown in Δ mark in the figure are blanking times, and these blanking times are essential to the constant resistance loop for the comparator to identify the resistance at phase transformation. Figure 6 shows the time chart of comparator switching, that depend on which region (R1, R2, or R3) the resistance value of ordered input is.

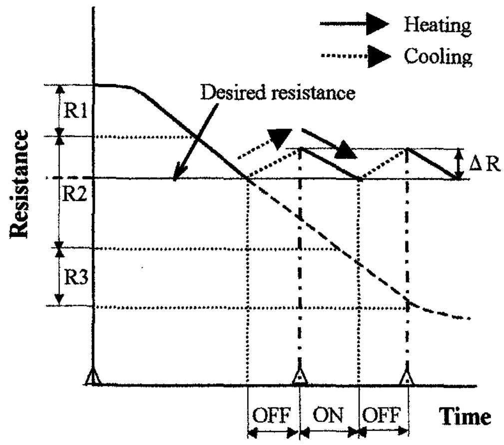

Fig.5 Control method of conduction-off time.

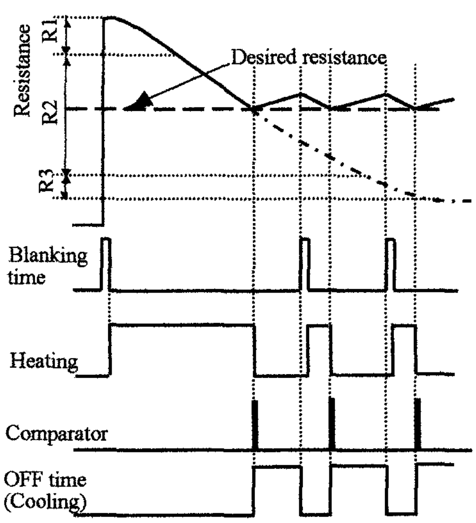

Fig.6 Time chart of comparator.

3. RESULTS AND DISCUSSION

3.1 Relationship between operating angle and desired input

Figure 7 shows the control characteristics of input voltage with the feedback system using a potentiometer as a position sensor and corresponding angular displacement. As shown in the figure, quite a good linearity is observed between the input voltage and the angular displacement throughout the range, without any hysteresis for input voltage's increase and decrease processes.

Fig. 8 shows the similar characteristics in the case of resistance control method when the voltage corresponding to the resistance of SMA is decreased from the supremum to the infimum and then increased. The reason why the characteristics in Fig.7 and Fig.8 differ in gradient (positive vs. negative slope) is that, with the resistance control method, angular disposition becomes minimum at the maximum input voltage corresponding to the resistance. In case of the resistance feedback, as shown in Fig.8, when resistance value is decreased from the maximum to the minimum and then increased back to the maximum, the angular displacement in the initial small value differs from that in the last small value because of the hysteresis characteristics shown in Fig.1.

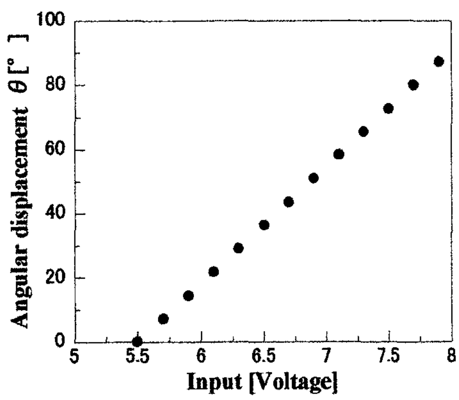

Fig.7 Control characteristics by potentiometer feedback.

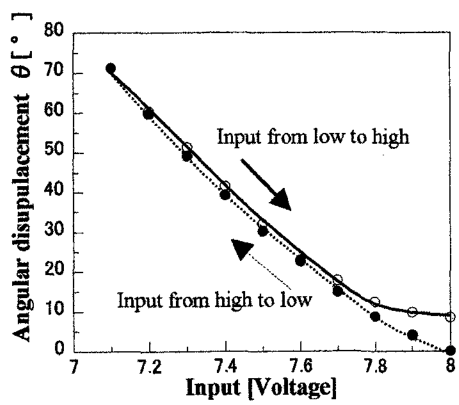

Fig.8 Control characteristics by resistance feedback.

This is considered to be because, in Fig.5, three areas of OFF time duration become longer with larger resistance value (i.e. smaller angular displacement) and resistance value is detected when temperature moves from high to low.

3.2 Response characteristics

Fig. 9 shows the response time characteristics of both the resistance feedback and the potentiometer feedback. The response time is defined by the time, when the system is started from the desired maximum angular displacement, required to reach the maximum angular displacement. As seen in the figure, the time required to reach the maximum angular displacement is 1.1 seconds longer in the resistance feedback system than in the potentiometer's case. The difference of response time is considered to be caused by the OFF time required to the resistance feedback.

3.3 Stability

Figure 10 shows the stability of the angular displacement for each of the three resistance regions, changing the OFF time (see Fig.5). Here, the stability is defined as the variation of angle (expressed in percentage) against the angular displacement when position is retained. This figure shows the difference in stability among the cases that OFF time is fixed throughout the total resistance range and the cases that OFF time is switched to two to three different values. The stability is 3.5% at maximum when the OFF time is fixed, but it is improved to 0.12% by applying three levels of OFF time.

4. CONCLUSION

A position control system using resistance feedback of SMA was produced and control characteristics such as position accuracy, response time and OFF time were investigated. The following conclusions were derived from results.

(1) Stable performance is obtained in the constant resistance position control system, by stopping the electric current for heating when the real-time resistance reaches the desired value and applying three different OFF-time durations in the course of initial, intermediary, and final stages of varying resistance.

(2) The resistance feedback system is compared with the potentiometer feedback system, and it is found that the latter is still superior in linearity, response characteristics and stability. However, it is shown that the positioning can be set and retained at an arbitrary position without using any outside sensor devices by using the method of setting 3 kinds of OFF times corresponding to 3 regions of resistance values ,and Blanking time.

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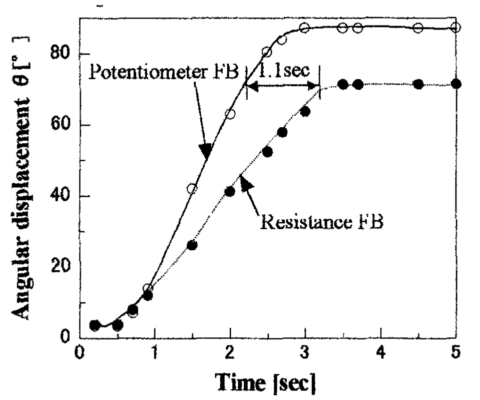

Fig.9 Response characteristics

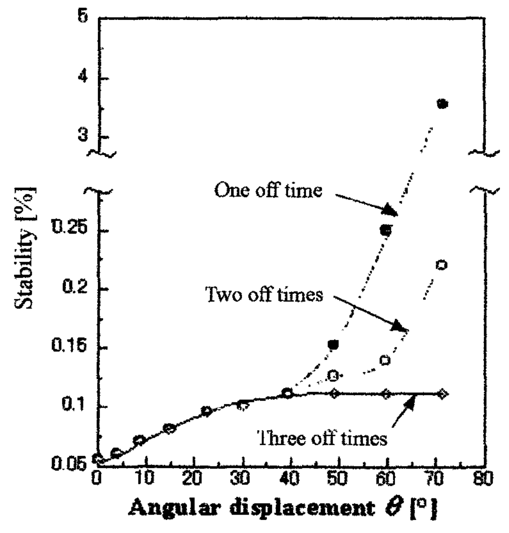

Fig.10 Effect of OFF time on stability in the resistance feedback system.

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