



HOKKAIDO UNIVERSITY

Title	Phase Resistance Feedback Control and Modeling of Thick SMA Actuators
Author(s)	李, 軍鋒
Degree Grantor	北海道大学
Degree Name	博士(工学)
Dissertation Number	甲第11169号
Issue Date	2013-12-25
DOI	https://doi.org/10.14943/doctoral.k11169
Doc URL	https://hdl.handle.net/2115/54652
Type	doctoral thesis
File Information	Junfeng_Li.pdf



PHASE RESISTANCE FEEDBACK CONTROL AND MODELING OF THICK SMA ACTUATORS

DOCTORAL DISSERTATION

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DIVISION OF HUMAN MECHANICAL SYSTEM AND DESIGN

GRADUATE SCHOOL OF ENGINEERING

HOKKAIDO UNIVERSITY

DECEMBER, 2013

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This doctoral thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text.

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December 2013

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DISSERTATION ABSTRACT

Title of dissertation submitted for the degree

Phase resistance feedback control and modeling of thick SMA Actuators

Shape memory alloy (SMA) actuators have great potential in niche applications where space, weight, cost and noise are crucial factors. These applications include mobile robots, microrobot manipulation, smart structures, and artificial muscles. Despite many of the advantages, they remain mostly as experimental actuators due to their perceived slow response speed, low accuracy and controllability. In the past, research had focused on position and force control of thin SMA wires, because they can be cooled fast in air and as it is easy to obtain rapid response speed for SMA actuators in this manner. Due to hysteresis and significant nonlinearities in the behavior of shape memory alloy actuators, it is difficult to obtain rapid response speed of SMA actuators, which have limited the application of these actuators, especially for thick SMA wires. In this thesis, effective control systems are applied to achieve rapid response speed control of SMA wire actuators.

In this thesis, experimental tests are conducted in chapter 3 to show the existence of latency duration during the heating and cooling process for thick SMA wires 0.5mm in diameter. The heating times (5s for SMA1 and 3s for SMA2) are decided to obtain the latency duration with ‘on-off’ binary control. It is important to avoid overheating of SMA wires which leads to long latency duration and slow to cool when the power is

turned off. In addition, the experimental results show that the ambient temperature has an effect on the cooling speed. Therefore, the ambient temperature needs to be stable when the experiments conducted.

Then, an approach is proposed in chapter 4 to design and control a thick SMA actuator to achieve rapid response speed control with two connected SMA wires. In the proposed method, a structure with two connected SMA wires is designed and then the concept of phase resistance is defined to use it as feedback in the response speed control system. Phase resistance feedback control (PRFC) minimizes cooling time by shortening the long latency duration of thick SMA wires. To accurately identify phase resistances, experiments showed that it is important to determine the major hysteresis loop. Experimental results that demonstrate the advantages and justify the concepts are also presented.

Subsequently, another method is proposed in chapter 5, the phase resistance with displacement feedback control (PRDFC), combining both the phase resistance and displacement as feedback, minimizes cooling time by shortening the long latency duration of thick SMA wires. PRDFC using segmented SMA wires shortens the latency duration of SMA wire, which coordinates with each other to make sure the continuity of output displacement. Two sets of experiment are tested using the step and ramp signals as reference input. Experimental results show that rapid response speed is achieved using this method in comparison with the case in which only displacement is used as feedback.

In chapter 6, a successful empirical relation is proposed in order to model the major and minor hysteresis loops of behavior for SMA actuators, which considers the amount of the austenite fraction transformed at a temperature based on Liang and Rogers model.

DISSERTATION ABSTRACT

Finally, the conclusions of the whole work are described and the future works are presented in chapter 7.

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CHAPTER 1:

INTRODUCTION

1.1 Background

A robot is a mechanical or virtual artificial agent, usually an electro-mechanical machine that is guided by a computer program or electronic circuitry. Robots can be autonomous or semi-autonomous. By mimicking a life like appearance or automating movements, a robot may convey a sense of intelligence or thought of its own. Robots have replaced humans in the assistance of performing those repetitive and dangerous tasks which humans prefer not to do, or are unable to do due to size limitations, or even those such as in outer space or at the bottom of the sea where humans could not survive the extreme environments. There are many kinds of robots, including mining robots, military robots, teleoperated robots and so on.

Robotics is the branch of technology that deals with the design, construction, operation, and application of robots, as well as computer systems for their control, sensory feedback, and information processing. These technologies deal with automated machines that can take the place of humans in dangerous environments or manufacturing processes, or resemble humans in appearance, behavior, and/or cognition. Many of today's robots are inspired by nature contributing to the field of bio-inspired robotics. Actuators are like the “muscles” of a robot, the parts which convert stored energy into movement. By far the most popular actuators are electric motors that spin a wheel or gear, and linear actuators that control industrial robots in factories. But there

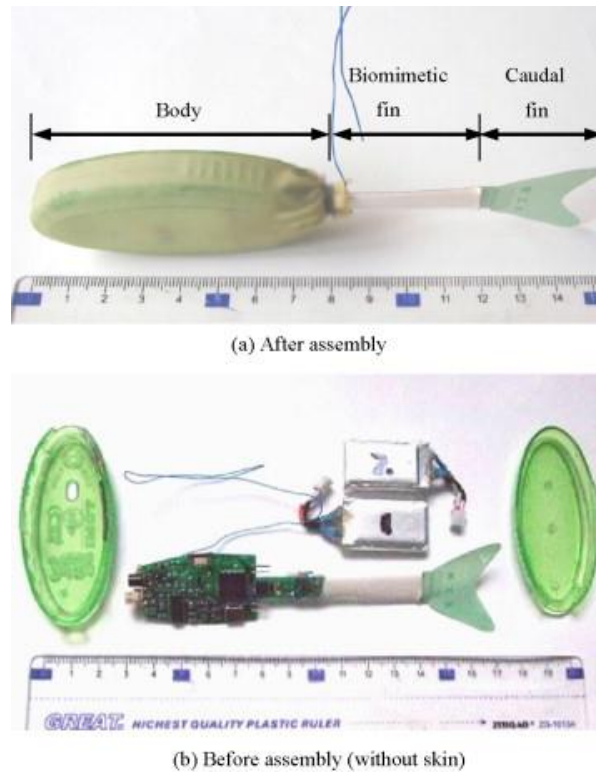


Fig. 1-2 Micro-robot fish prototype [1]

Following this trend, factors such as power consumption, work density, costs and space constraints gain increased importance in the selection of suitable technologies. However, conventional actuators, including electric motors, pneumatic and hydraulic actuators, suffer a large reduction in power that they can deliver as they are scaled down in size and weight. This constraint has led to the emergence and development of novel actuator technologies such as piezoelectric actuators, electrostatics, magnetostrictive materials and shape memory alloys (SMA). Wang et al. proposed a fish robot actuated by Shape Memory alloys [1], Fig. 1-1 and Fig. 1-2 show the details of fish robot.

Shape memory alloys (SMA) are metallic alloys which deform at low temperatures and return to the original undeformed state when heated to higher temperatures. The shape memory effect is a consequence of a reversion in the crystalline structure between the low temperature and high temperature phases, which are respectively called the

martensite and the austenite of the SMA. The martensite phase is nonsymmetric and relatively soft, while the austenite phase is symmetric and relatively hard and has a much higher Young's Modulus. Heating the SMA can be done via Joule heating, which is resistively heating the material using electric current. Of all the SMAs that have been discovered so far, NiTi shape memory alloys, also known as Nitinol, have proven to be the most flexible and successful in engineering applications. One of the ways SMAs are commonly used is in the form of wires. Already, SMA have been used in a variety of actuation applications because of advantages such as excellent power-to-mass ratios, reliability, and silent actuation, such as endoscope (Fig. 1-3).

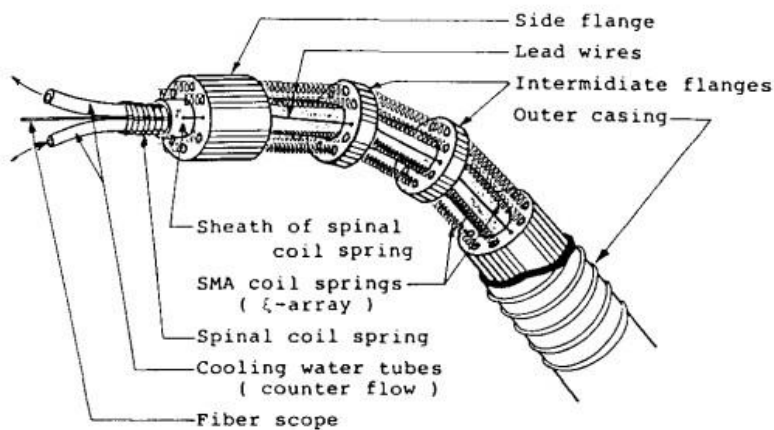


Fig.8 Inner structure of active endoscope (for unit segment)

Fig. 1-3 Endoscope actuated by SMA wires [2]

Ikuta, Tsukumoto and Hirose proposed a control system for a shape memory alloy (SMA) servo actuator, and its application to a unique medical tool [2]. It is thought that the electric resistance value of an SMA can be utilized to monitor the transformation of the SMA directly. Therefore, an antagonistic transformation control scheme using

electric resistance feedback is proposed and is verified by several experiments. The bending angle of each segment can be controlled individually from outside by using antagonistic electric resistance feedback without any motion sensors. Featherstone and Teh proposed a method for improving the speed of actuators based on SMA by increasing the rate at which an SMA element can safely be heated [3]. The method consists of measuring the electrical resistance of an SMA element, calculating a maximum safe heating current as a function of measured resistance, and ensuring that the actual heating current does not exceed this maximum value. In effect, resistance is being used as a form of temperature measurement, and the maximum safe heating current is designed to prevent overheating. Experimental results show a substantial increase in the maximum velocity attainable by this robot, without any change in the cooling regime, purely as a result of faster heating.

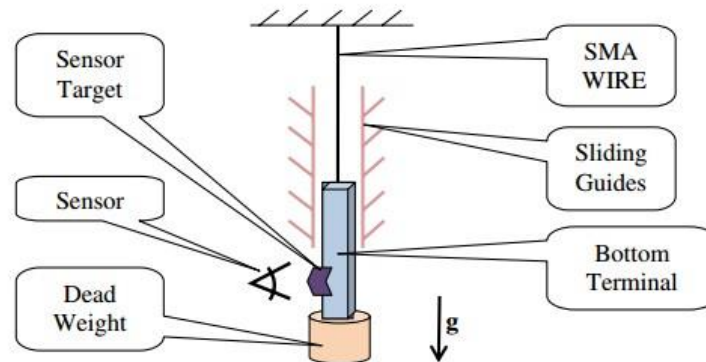


Fig. 1-4 An illustration of the mechanical setup with high voltage [4]

When the SMA wire is applied in fast moving robots, the response speed of the actuator is important, especially for robots which need thick SMA wires to provide large forces. However, thick SMA wires are accompanied by large latency durations which

slow down the reaction speed of the SMA actuators. Due to the slow speed caused by hysteresis phenomena in SMA which limits the practical application as actuators, many researches had focused on improving the response speed of the SMA.

Vollach and Shilo explored the capabilities of a fast one-directional actuation mode based on one-occasional rapid Joule heating of SMA elements [4]. For this purpose, a unique experimental system (Fig. 1-4) has been developed that applies a high-voltage electric pulse to a detwined NiTi wire and measures the resulting displacement due to the martensite to austenite phase transformation. The research demonstrates the great potential of SMA for applications that require high speeds and large displacements one-occasional actuation. However, this method demands maximum current (300 A) to heat the SMA, which is not practically available for application.

As shown in Fig. 1-5, Selden, Cho and Asada proposed the definition of state transition threshold temperatures and calculated the latency duration when the temperature increases from T_C to T_{CH} and decreases from T_H to T_{HC} [5]. In steady of investigation the relationship between latency duration and phase transformation temperature of SMA, the relationship the latency duration and output displacement is investigated in chapter 3.

In addition, a method eliminated the latency duration associated with phase transition of SMA actuators in proposed. As shown in Fig. 1-6, this control method is implemented using the Peltier effect thermoelectric devices for selective segment-by-segment heating and cooling. However, due to thermal conductivity along the wire, it might be troublesome to regulate adjacent segments at different temperatures. Then, segments are heated and cooled to extreme temperature. there is heat transfer between adjacent segments. In addition, one potential limitation to the experimental

apparatus built with Peltier effect is that segments of a SMA wire may shift to adjacent units, as the SMA wire shrinks and expands. This may cause some error when an adjacent segment at a different thermal state is brought to the neighboring segment. The worst case scenario is that every pair of adjacent segments takes different thermal states. Another potential limitation is that more energy will be needed to heat SMA since the Peltier needs to be heated first compared with heating the SMA by Joule heating. At last, the experimental apparatus is heavy because of many Peltier models in the apparatus. However, these limitations caused by the Peltier models can be eliminated using electricity to heat the SMA actuators, which are demonstrated in chapter 4. Theoretically, both latency durations can be shortened which is demonstrated. However, due to the electricity is used to heat the SMA wire in this thesis, the latency duration when temperature increases from martensite finish to austenite start is short compared with the latency duration when the SMA is cooled by air and temperature decreases from austenite finish to martensite start. Only the latency duration when temperature decreases from austenite finish to martensite start is shortened by the proposed method.

Other researches about achieving fast response speed and using resistance as feedback will be introduced in chapter 4 as well. The detailed information about how to implement Joule heat to shorten the latency duration during the position control using phase resistance and displacement as feedback is discussed in chapter 5.

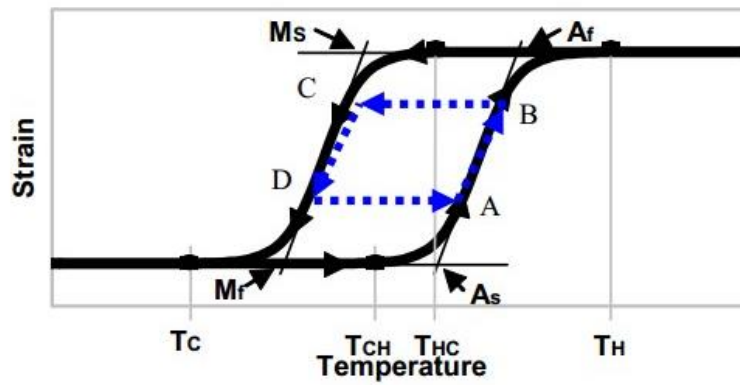


Fig. 1-5 Strain-temperature characteristics [5]

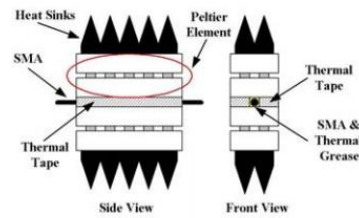
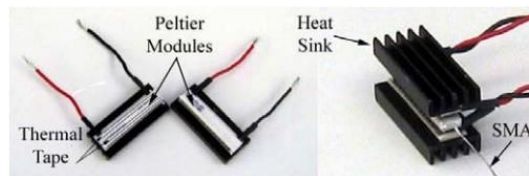
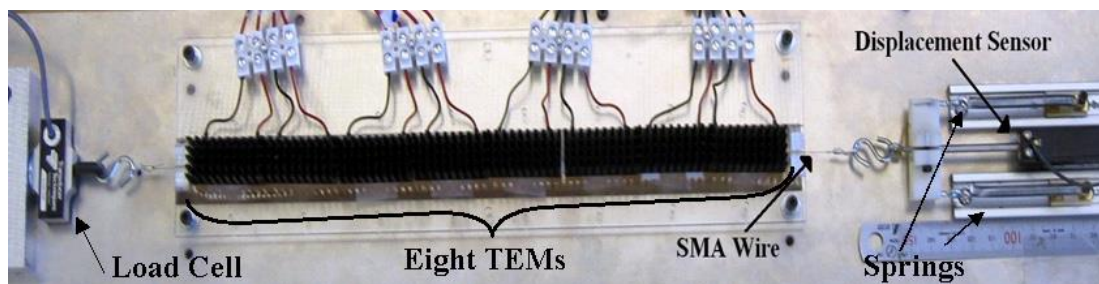


Fig. 7 A schematic of the heating and cooling system for controlling the temperature of one segment.



(i)



(ii)

Fig. 1-6 (i) Peltier sandwich structure;
(ii) Photo of experiment setup of SMA actuator [5]

1.2 Research Objectives and Approach

Due to hysteresis effect and nonlinear relationship, SMA actuators have generally been considered to be slow, inaccurate and difficult to control continuously. The primary objective of this research is to demonstrate that more rapid response speed of SMA actuators can be achieved compared with the conventional method using new design and implementation of practical and effective control systems.

Two approaches proposed here that have been adopted for achieving rapid response speed. One is phase resistance feedback control (PRFC), which uses two SMA wires and the results with PRFC will be compared with that of traditional control method using only one SMA wire applied in PRFC. The other is phase resistance with displacement feedback control (PRDFC), which uses two SMA wires as well and the results with PRDFC will be compared with that of traditional control method using one SMA wire. The total length of SMA wire used in both experimental tests for the second approach is the same.

In order to apply the phase resistance as feedback to obtain rapid response speed, a SMA actuator using two SMA wires which are connected together using insulation joint to prevent short circuiting is proposed. Then, phase transformation resistances of SMA wires are identified using experimental data. The critical aspect of the proposed method is to shorten the latency time caused by hysteresis effect of SMA actuators [5]. The SMA wires are heated separately to prevent interruption arisen from power. The heating and cooling processes depends on the phase resistances of both wires. And experimental tests are conducted to testify the effectiveness of the proposed methods.

1.3 Outline of Thesis

This thesis is divided into seven chapters and organized in the following manner.

In chapter 2, some background information on SMAs, including more detailed descriptions of their phases and the phase transformations, as well as the various arrangements illustrating how SMAs are used as actuators.

In chapter 3, an experimental setup is built in order to test the latency durations of SMA wires. Detailed information about the experimental setup is demonstrated and the results of two SMA wires show whether the latency duration exists during both the heating and cooling processes and the ambient temperature has an effect on the cooling speed or not. In addition, a criteria is decided to determine the martensite start displacement during the cooling process.

In chapter 4 and chapter 5, PRFC and PRDFC are proposed here to achieve rapid response speed of SMA actuator with two connected SMA wires, respectively. The basic theory of PRFC and PRDFC are introduced and the control systems of PRFC demonstrate how they work using phase resistances as feedback. Results with PRFC and PRDFC are compared with that of binary control and traditional control method.

In addition, in chapter 6, a model is proposed to try to represent the major and minor hysteresis loops of behavior for SMA actuators. The simulation as well as the experimental results will be presented and compared.

Finally, in chapter 7, a summary of the research achievements will be provided together with some discussion of future works

CHAPTER 2:

NICKEL-TITANIUM SHAPE MEMORY ALLOYS

In the 1930s, the first reported steps towards the discovery of the shape-memory effect were taken. According to Otsuka and Wayman, A. Ölander discovered the pseudoelastic behavior of the Au-Cd alloy in 1932. Greninger and Mooradian (1938) observed the formation and disappearance of a martensitic phase by decreasing and increasing the temperature of a Cu-Zn alloy. A decade later, the basic phenomenon of the memory effect governed by the thermoelastic behavior of the martensite phase was widely reported by Kurdjumov and Khandros (1949) and also by Chang and Read (1951).

In 1962-1963, the nickel-titanium alloys were developed by the United States Naval Ordnance Laboratory and commercialized under the trade name Nitinol (an acronym for Nickel Titanium Naval Ordnance Laboratories). Their remarkable properties were discovered by accident. A sample that was bent out of shape many times was presented at a laboratory management meeting. Muzzey, one of the associate technical directors, decided to see what would happen if the sample was subjected to heat and held his pipe lighter underneath it [6]. To everyone's amazement the sample stretched back to its original shape.

There is another type of SMA, called Magnetic shape-memory alloys (MSMAs). Due to martensitic phase transformation, MSMAs are ferromagnetic materials which exhibit large strains under the influence of an applied magnetic field.

MSMAs, with near-stoichiometric Ni₂MnGa being the most studied example, differ from other magnetostrictive materials, such as Terfenol-D and Galfenol, as they produce much larger strains by twinning, sometimes as large as 9%, under relatively low bias magnetic fields. The mechanism is based on the magnetic anisotropy of the material. As other SMA which change phase between austenite and martensite with the application of thermal energy, MSMAs produce a similar phase transformation between martensite 1 and martensite 2 (the two variants). Few models have been developed which describe the constitutive response of MSMAs. To describe the materials behavior, thermodynamic modeling is typically used. A shift in the direction of magnetization is produced when applying a stress to a fully strained element exposed to a bias field because of the nature of MSMAs. The magnitude of this shift changes according to the strength of the applied field and material properties. Using Faraday's law of induction, MSMAs may be used for energy harvesting using a pickup coil, or inductor [7-8].

Shape-memory alloys are typically made by casting, using vacuum arc melting or induction melting. These are special techniques used to keep impurities in the alloy to a minimum and ensure the metals are well mixed. The ingot is then hot rolled into longer sections and then drawn to turn it into wire. The way in which the alloys are “trained” depends on the properties wanted. The “training” dictates the shape that the alloy will remember when it is heated. This occurs by heating the alloy so that the dislocations re-order into stable positions, but not so hot that the material recrystallizes. They are heated to between 400°C and 500°C for 30 minutes. They are then shaped while hot and are cooled rapidly by quenching in water or by cooling with air. The manufacturing equipment can be found in many references, such as [9-10]. Concerning about manufacturing routes of SMA, in the past, many research had focused on this field

[11-12].

2.1 Phase Transformation Temperature of SMA

The austenite phase transformations of the alloy can be characterized by four transformation temperatures:

T_{AS} : Austenite start temperature

T_{AF} : Austenite finish temperature

T_{MS} : Martensite start temperature

T_{MF} : Martensite finish temperature

The martensite fraction can be used to represent the amount of martensite phase in the alloy during the heating and cooling processes [13]. As shown in Fig. 2-1, with a temperature less than T_{MF} , the NiTi alloy consists only of the martensite phase. As the temperature increases beyond T_{AS} , austenite begins to form in the alloy and when the temperature exceeds T_{AF} , the alloy is primarily in the austenite phase. As the alloy is cooled, martensite begins to form when the temperature drops below T_{MS} , and when the temperature reaches T_{MF} , the alloy is again fully martensitic.

The transition between the austenite and martensite phases can be characterized by a wide thermal hysteresis loop, especially for thick SMA wires. The hysteresis varies according to the alloy system. For example, the temperature hysteresis is generally between 30°C-50°C for NiTi alloys. During phase transitions between martensite and austenite, most of the physical properties of SMAs vary, including Young's Modulus, electrical resistance, heat capacity and thermal conductivity. In the possible range where both martensite and austenite co-exist, nonlinearities and hysteresis are prominent, and

they are influenced by material composition, processing and the number of activated cycles [14].

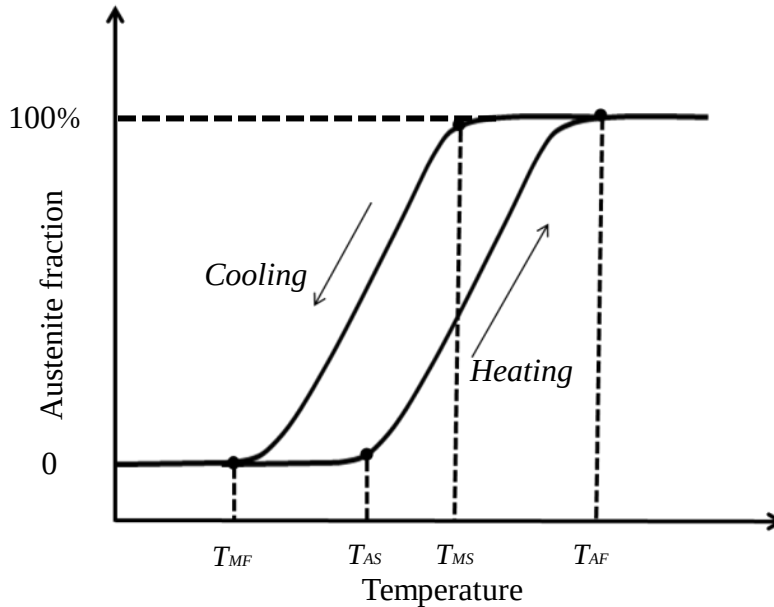


Fig. 2-1 Schematic of austenite fraction-temperature hysteresis

2.2 Two Different Shape-Memory Effects

In addition to common shape change effects such as elastic and plastic deformations, as well as thermal expansion and contraction, SMA also exhibit three shape memory characteristics. Two common effects are one-way and two-way shape memory. A schematic of the effects is shown below.

As shown in Fig. 2-2 and Fig. 2-3, the procedures are very similar: starting from martensite (a), adding a reversible deformation for the one-way effect or severe deformation with an irreversible amount for the two-way (b), heating the sample (c) and cooling it again (d).

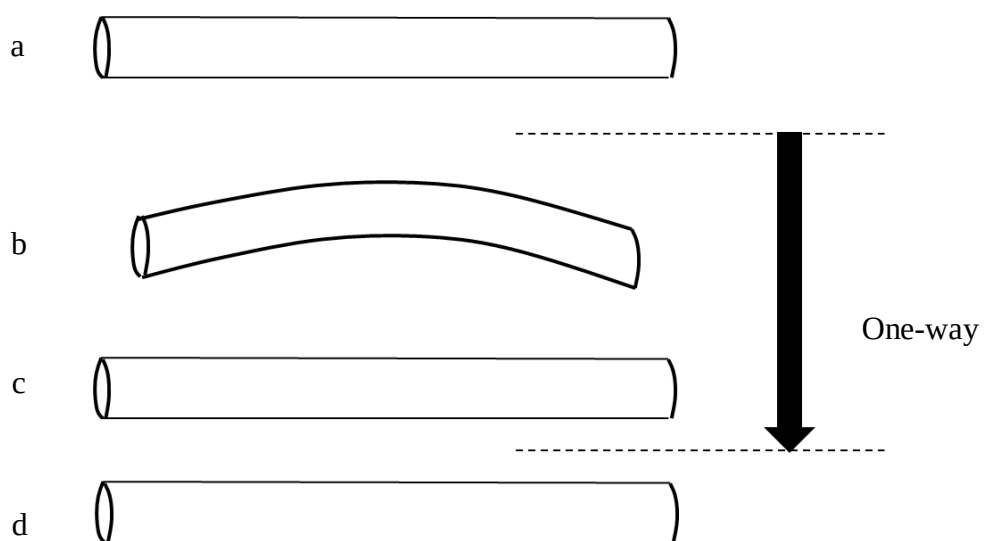


Fig. 2-2 Schematic for one way of SMA

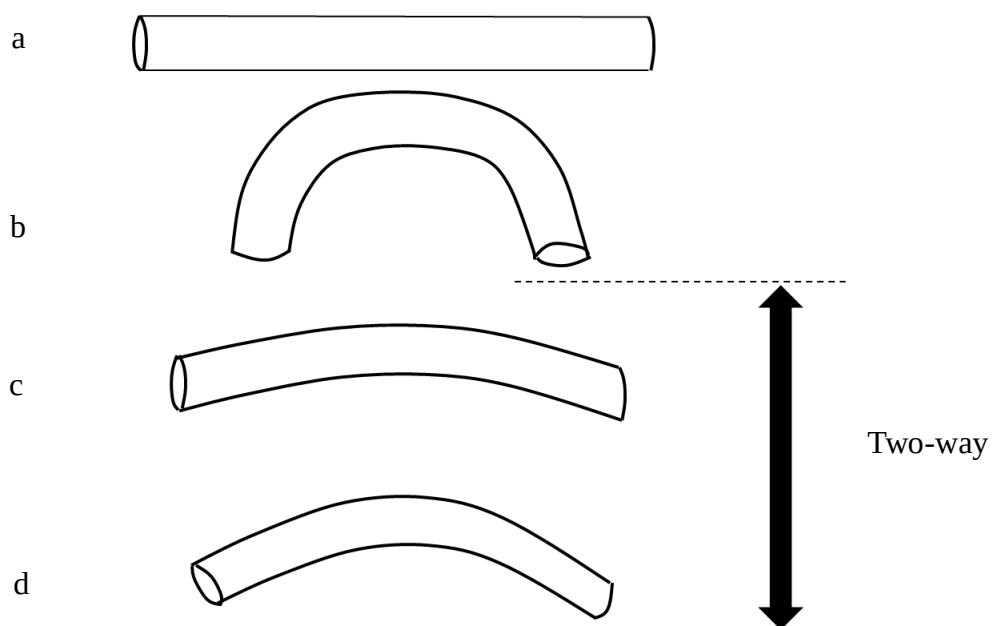


Fig. 2-3 Schematic for two ways of SMA

2.2.1 One-way of SMA

NiTi alloys exhibit the Shape Memory Effect (SME) when it is deformed while in the martensitic phase and then unloaded while still at a temperature below T_{MF} . If it is subsequently heated above T_{AF} , it will regain its original shape by transforming back into the parent austenitic phase. When the metal cools again it will remain in the hot shape, until deformed again. Since martensite variants have been reoriented by stress, the reversion to austenite produces a large transformation strain having the same amplitude but the opposite direction with the inelastic strain. With the one-way effect, cooling from high temperatures does not cause a macroscopic shape change. A deformation is necessary to create the low-temperature shape. On heating, transformation starts at T_{AS} and is completed at T_{AF} (typically 2°C to 20°C or hotter, depending on the alloy or the loading conditions). T_{AS} is determined by the alloy type and composition and can vary between -150°C and 200°C.

The above described phenomenon is called one-way shape memory effect (or simply, shape memory effect) because the shape recovery is achieved only during heating.

2.2.2 Two-way of SMA

The two-way shape memory effect is less pronounced than the one-way effect and usually requires training. In the shape memory effect discussed above, what is remembered was the shape of the parent phase only; but, under certain conditions it is possible to have two different shapes: one at low temperatures, and one at the high-temperature shape. This effect was first called “the reversible shape memory effect” [15-16], but now it is called two-way shape memory effect.

SMA can be trained to exhibit the two-way effect using two methods, one is spontaneous load-assisted induction, and the other is external load-assisted induction

[17]. However, the shape change obtained is in practice less than that of the one-way effect.

2.2.3 Pseudo-elasticity

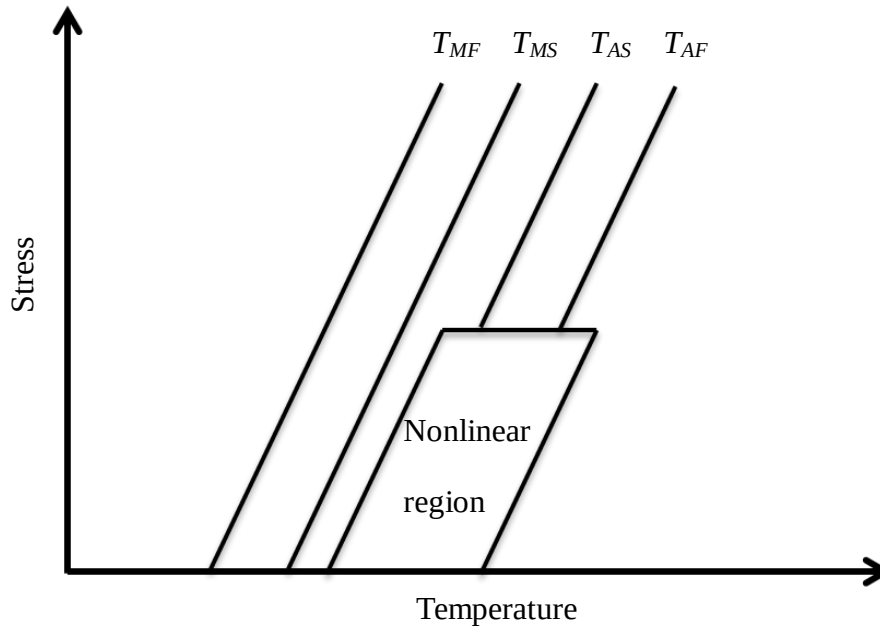


Fig. 2-4 Schematic of stress VS temperature

There is another effect, pseudo-elasticity, also known as ‘super-elastic Effect (SE)’. It is the shape recovery associated with mechanical loading and unloading of SMAs at temperatures above T_{AF} and is associated with stress-induced martensitic transformation and reversal to austenite upon unloading.

The stress dependence of the four transition temperatures can be represented as [18]:

$$\frac{d\sigma}{dT_r} = \frac{-\Delta H}{T} \varepsilon_0 \quad (2-1)$$

where σ is the applied stress; T_r is the transformed temperature; ΔH is the transformation latent heat; T is the temperature and ε_0 the strain resolved along the direction of the applied stress.

As is shown in Fig. 2-4, the temperatures of T_{AS} and T_{AF} are highly nonlinear at low stress levels. Then, the stress dependence of the transformation temperatures can be expressed as a generalized temperature, given by [19]:

$$\frac{d\sigma}{dT} = \frac{1}{c_m}, \text{ or } T = c_m\sigma + T_0 \quad (2-2)$$

where $1/c_m$ is the stress rate, T is the stress dependent transformation temperature and T_0 is the zero stress transformation temperature.

2.3 Micro and Macro Analysis of SMA

Concerning about the SMA, it is necessary to introduce changes of crystal structures and macro shapes during the heating and cooling processes. Many metals have several different crystal structures at the same composition, but most metals do not show the shape memory effect. The special property that allows SMA to revert to their original shape after heating is that their crystal transformation is fully reversible. In most crystal transformations, the atoms in the structure will travel through the metal by diffusion, changing the composition locally, even though the metal as a whole is made of the same atoms. A reversible transformation does not involve this diffusion of atoms, instead all the atoms shift at the same time to form a new structure, much in the way a parallelogram can be made out of a square by pushing on two opposing sides. At different temperatures, different structures are preferred and when the structure is cooled through the transition temperature, the martensitic structure forms from the austenitic phase.

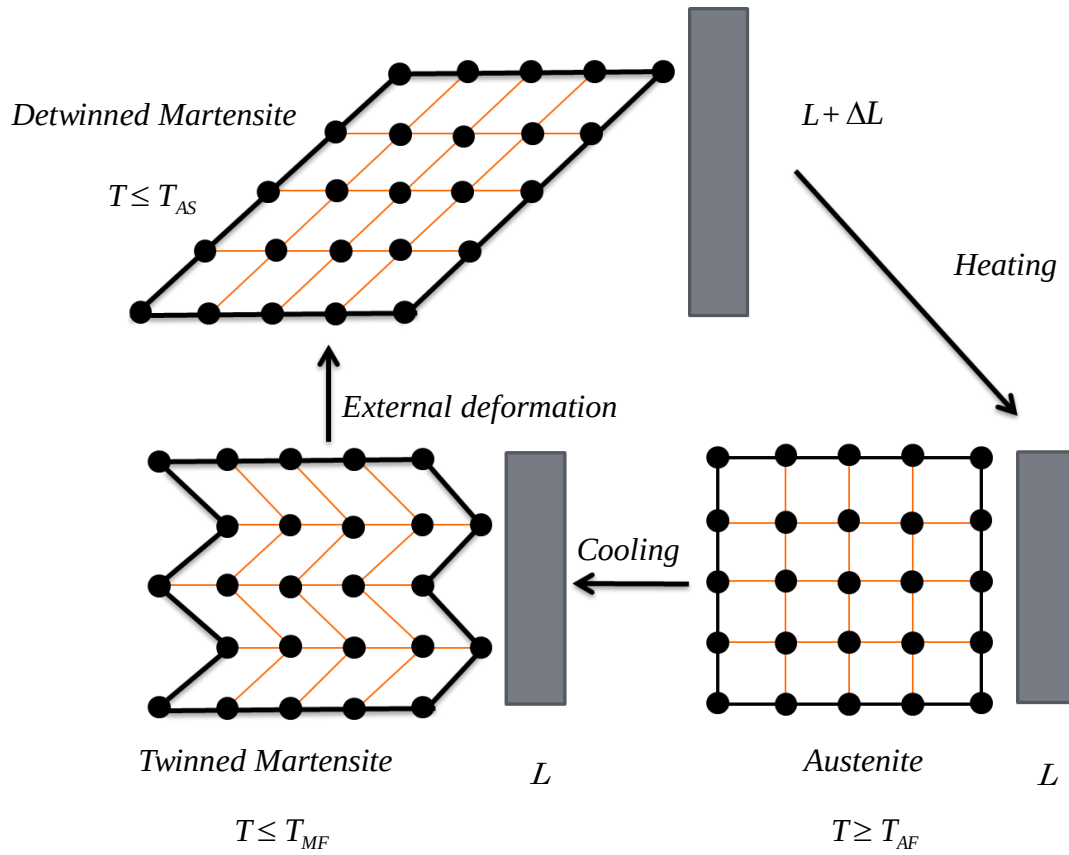


Fig. 2-5 Schematic of micro and macro phenomenon of SMA

The unique property of Ni-Ti alloys is shape memory effect, which can be explained in a rough 2-dimensional approximation of the underlying atomic rearrangements, including the micro and macro analysis of SMA. As shown in Fig. 2-5, the atomic lattice is primarily in the martensite phase when the temperature is less than T_{AS} . The length of SMA wire is $L + \Delta L$ when it is applied external force; as the temperature exceeds T_{AS} , austenite layers begin to form. Then, austenite phase completes when the temperature exceeds T_{AF} . The atomic lattice is primarily in the austenite phase. The length of SMA wire is L , which is the original length without applying external force; as the alloy cools, martensite layers begin to form when the temperature decreases below T_{MS} and the atomic lattice is primarily in the martensite phase when the

temperature reaches T_{MF} . The length is practically unchanged and it is the same as in the austenite phase [20].

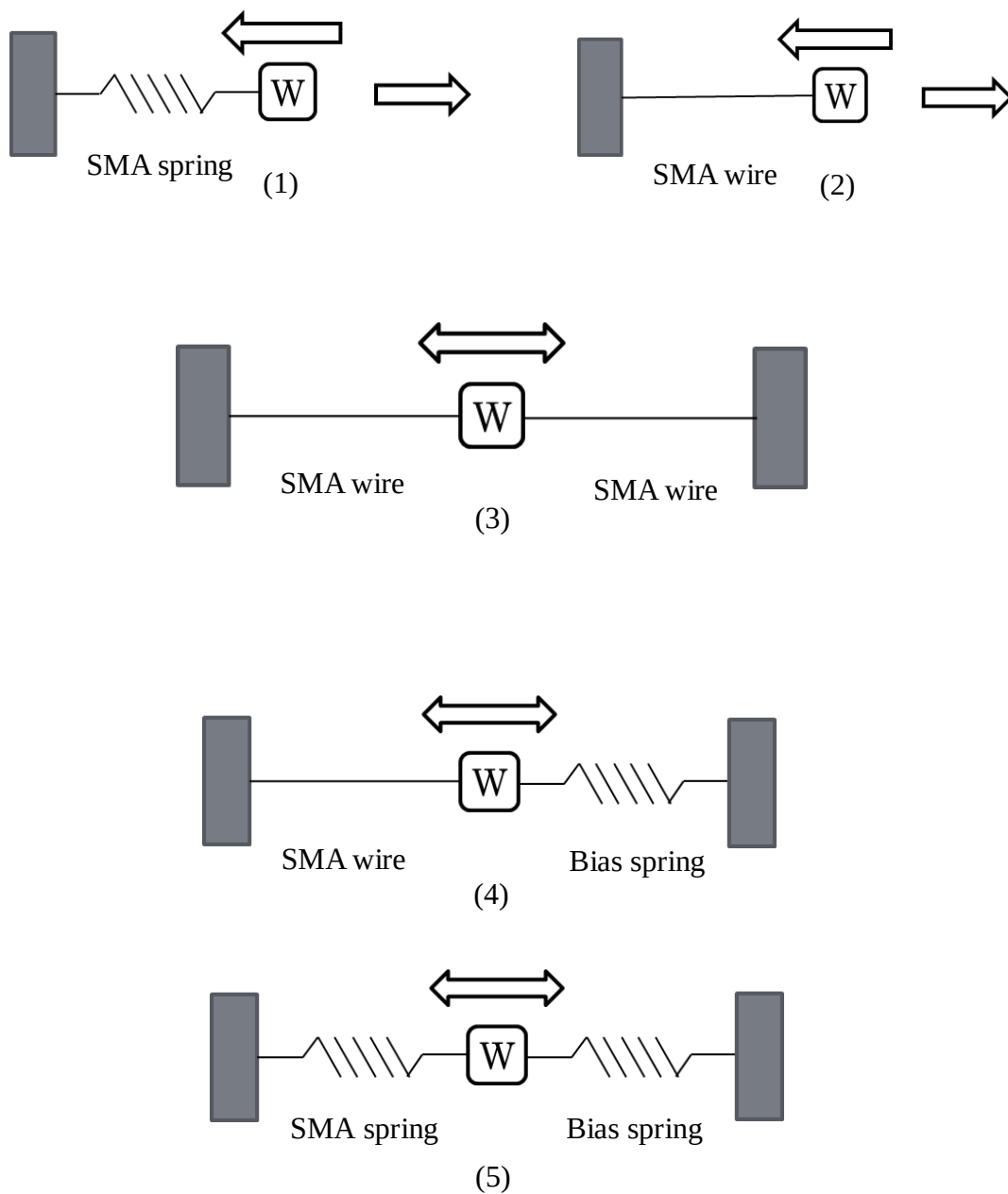
2.4 SMA Actuators

SMA is used as actuators because of the following advantages.

SMA actuators offer the highest power-to-weight ratio compared with different types of actuator technologies [21]. Since An SMA actuator only uses the shape recovery of the alloy and it can be actuated directly via Joule heating, it does not require any reduction gear system nor other moving parts, resulting in saving material, production, maintenance costs and easy miniaturisations of simple actuator systems [22]. In addition, there is no need for friction mechanisms in SMA actuators, such as reduction gear, it avoids the production of dust particles, sparks and noise. These properties make SMA actuators highly attractive for miniature applications. Therefore, it is extremely suitable for areas, such as microelectronics, biotechnology and medical applications, to apply SMA as actuators.

SMA have many advantages over traditional actuators, but do suffer from a series of limitations that may impede practical application [23]. Since SMA actuators are typically actuated electrically, deactivation typically occurs by free convective heat transfer to the ambient environment. Consequently, SMA actuation is typically asymmetric, with a relatively fast actuation time and a slow deactuation time. SMA are subject to structural fatigue [24-26], which is a failure mode by which cyclic loading results in the initiation and propagation of a crack. It eventually results in catastrophic loss of function by fracture. The physics behind this fatigue mode is accumulation of

microstructural damage during cyclic loading. In addition, SMA are also subject to functional fatigue, whereby the SMA do not fail structurally, but, due to a combination of applied stress, and/or temperature, lose the ability to undergo a reversible phase transformation. At last, SMA actuators are typically actuated electrically by Joule heating. If the SMA are used in an environment where the ambient temperature is uncontrolled, unintentional actuation by ambient heating may occur.



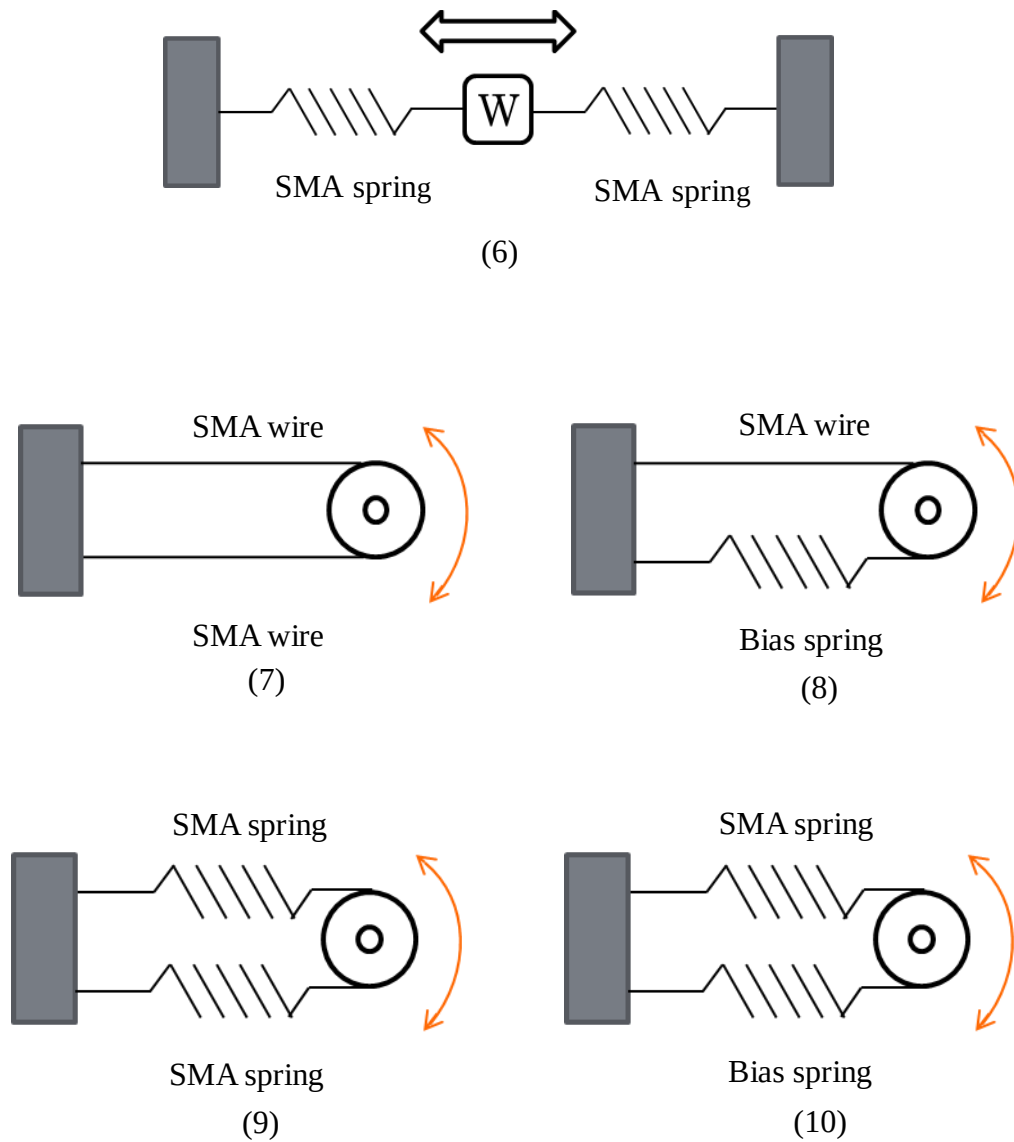


Fig. 2-6 Schematic of different SMA actuators

For SMA actuators, SMA wire or spring is used as actuator in practical application in order to obtain light and tight manipulators. Because SMA actuators utilize the one-way effect and can only contract in one direction, it is necessary to provide a biasing force to pull it back to the original length using a dead weight, a bias spring, or another SMA element in a differential arrangement. According to [27-28], the primary actuator joint applications can be divided into ten basic types, as shown in Figure 2-6.

2.5 Literature Overview

2.5.1 Modeling of SMA

To simulate the behavior of SMAs and as a control design aid, numerous models are proposed to represent or explain the characteristics of SMAs, most notably in terms of their thermomechanical relations and the hysteresis effects. Kuribayashi experimentally observed the relationship between small variations in the force and strain of an SMA wire, which can be expressed by the following mathematical model [29].

$$\Delta f = a\Delta u + b\Delta x \quad (2-3)$$

where Δf , Δu , and Δx are the force, voltage, and strain, respectively. a and b are gain constants. Regarding the static model of Eq. (2-3) as the steady state of a dynamic system, a dynamic model by adding first order terms for $G(s)$ and $H(s)$ in the Laplace domain is proposed in the following relationship.

$$\Delta f(s) = aG(s)\Delta u(s) + bH(s)\Delta x(s) \quad (2-4)$$

A thermomechanical law that governs the stress-strain behavior of the SMA element was proposed by Tanaka, which is expressed by [30-31]

$$\dot{\sigma} = D\dot{\eta} + \Theta\dot{T} + \Omega\dot{\xi} \quad (2-5)$$

where σ is the Piola-Kirchhoff stress, η is the Green strain, T is the temperature, and ξ is the martensite ratio. D , Θ , and Ω are respectively the elastic modulus, the thermoelastic, and the transformation tensor.

The phase transformation is described by exponential functions, including heating and cooling transformation processes. The ratio of martensite ξ of the cooling process for austenite to martensite can be given by [32]

$$\xi = 1 - \exp[-a_M(T_{MS} - T) - b_M\sigma] + \xi_0 \quad (2-6)$$

where a_M and b_M are positive material parameters, ξ_0 is the initial volumetric fraction when phase transformation takes place. For the reverse transformation, from martensite to austenite, it can be expressed by

$$\xi = \xi_0 \exp[-a_A(T - T_{AS}) - b_A\sigma] \quad (2-7)$$

where a_A and b_A are positive material parameters.

Based on the Tanaka's original model, Boyd and Lagoudas rewrite Tanaka's original model, for a three-dimensional theory construction [33]. The constants a_M, b_M, a_A , and b_A are estimated by

$$a_M = \frac{2 \ln(10)}{T_{MS} - T_{MF}}, \quad b_M = \frac{a_M}{C_M}, \quad a_A = \frac{2 \ln(10)}{T_{AF} - T_{AS}}, \quad b_A = \frac{a_A}{C_A} \quad (2-8)$$

Liang and Rogers proposed an alternative equation to represent the martensite fraction based on cosine function [34]. This model was applied to acoustic vibration control studies and its results show good agreement with experimental data [35-36]. The model can be given by

$$\xi = \frac{1 - \xi_0}{2} \cos[A_M(T - T_{MF} - \frac{\sigma}{C_M})] + \frac{1 + \xi_0}{2}, \quad \text{Heating process} \quad (2-9)$$

where $C_M(T - T_{MS}) < \sigma < C_M(T - T_{MF})$, C_M is a material parameter.

$$\xi = \frac{\xi_0}{2} \cos[A_A(T - T_{AS} - \frac{\sigma}{C_A})] + 1 \quad \text{Cooling process} \quad (2-10)$$

where $C_A(T - T_{AF}) < \sigma < C_A(T - T_{AS})$, C_A is a material parameter. And the A_M and A_A can be defined by

$$A_M = \frac{\pi}{T_{MS} - T_{MF}}, \quad A_A = \frac{\pi}{T_{AF} - T_{AS}} \quad (2-11)$$

Since an antagonistic arrangement of SMA actuators was used in Grant's experiment, a single linear transformation kinetics equation without hysteresis effect which

simplifies the model is proposed [37].

$$\xi = \begin{cases} 1 & T < T_{AS} \\ \frac{T_{AF} - T}{T_{AF} - T_{AS}} & T_{AS} \leq T \leq T_{AF} \\ 0 & T > T_{AF} \end{cases} \quad \text{Heating process} \quad (2-12)$$

Dutta and Ghorbel proposed a differential hysteresis model to represent the SMA behavior [38]. The operation of the SMA actuator involves different physical phenomena, such as heat transfer, phase transformation with temperature hysteresis, stress-strain variations and electrical resistance variation accompanying the phase transformation. The martensite fraction model of major hysteresis loop is given by

$$v_{+/-} = h_{+/-}(u) = \int_{-\infty}^u g_{+/-}(u') du' = \frac{1}{2} [1 + \operatorname{erf}(\frac{u - \mu_{+/-}}{\sigma_{+/-} \sqrt{2}})] \quad (2-13)$$

where subscripts + and – denote heating and cooling curves, respectively. $\sigma_{+/-}$ and $\mu_{+/-}$ are constants. g_+ and g_- are slops functions which can be given by Duhem model [39]

$$\begin{cases} \dot{v} = g_+(u(t), v(t))(\dot{u})^+ - g_-(u(t), v(t))(\dot{u})^- \\ v(0) = v_0 \end{cases} \quad (2-14)$$

where $(\dot{u})^\pm = (|\dot{u}| \pm \dot{u})/2$, and $g_+, g_- \in C^0(\mathbb{R}^2)$. $u(t)$ and $v(t)$ are the input and output.

The slop function of the minor hysteresis loop is given by

$$g_{+/-}(u) = \frac{n_{i+/-}}{\sigma_{+/-} \sqrt{2\pi}} \exp(-\frac{(u - \mu_{+/-})^2}{2\sigma_{+/-}^2}) \quad (2-15)$$

where $i = 1 \cdots N, n_{i+/-} \in [0, 1]$.

The resistance of austenite or martensite phase is given by

$$R_{A/M} = \frac{4L_0(1+2\varepsilon)}{\pi d_0^2} \rho_{A/M}(T) \quad (2-16)$$

$\rho_{A/M}(T)$, the electrical resistivity of austenite or martensite phase, can be expressed by

$$\rho_A(T) = p_1 + p_2 \exp(-p_3(T - T_{amb})) \quad (2-17)$$

$$\rho_M(T) = (q_1 - q_2 T) [1 + \operatorname{erf}(\frac{T - m_1}{m_2})] + \sum_{i=0}^9 a_i (T - T_{amb})^i \quad (2-18)$$

where $p_1, p_2, p_3, q_1, q_2, m_1, m_2, T_{amb}$, and $a_i (i = 0, \dots, 9)$ are constant parameters.

Then, the SMA wire electrical resistance R of major hysteresis loop is given by

$$\frac{1}{R} = \frac{1 - v_{+/-}}{R_A} + \frac{v_{+/-}}{R_M} \quad (2-19)$$

Concerning about other models to represent the hysteresis effect of smart material, Preisach modeling of SMA hysteresis is one of the most successful mathematical models [40-46].

This model can be considered as an operator which integrates infinite weighted elementary hysteresis operators over a two dimensional region and it can be expressed by

$$u(t) = H[v(t)] = \iint_T \mu_{\alpha\beta} \gamma_{\alpha\beta}[v(t)] d\alpha d\beta \quad (2-20)$$

where $v(t)$ is the input of hysteresis. $u(t)$ is the output of hysteresis. H is an operator to transform $v(t)$ to $u(t)$. $\gamma_{\alpha\beta}$ is the output of an elementary hysteresis operator subjected to $v(t)$. $\mu_{\alpha\beta}$ is a density function of variables of α and β to scale outputs of relays. T is Preisach plan over hysteresis occurs, which is defined as

$$T = \{(\beta, \alpha) \in R^2 : v^+ \geq \alpha \geq \beta \geq v^-\} \quad (2-21)$$

where α and β denote the increasing and decreasing $v(t)$, respectively.

$v(t) \in [v^-, v^+]$ indicates the hysteresis input domain.

Generally, the inverse model is derived and used to obtain accurate position tracking results in position control system [47]. The inverse Preisach model can be expressed according to the following algorithm.

For a given output $u(\theta)$ at a time θ and a known $v(t < \theta)$ and $u(t < \theta)$ of a hysteresis, increase or decrease $v(t)$ by steps of $idv, i = 1, \dots, n$, until calculated output of the Preisach operator be mostly close to $u(\theta)$, until

$$H[v(t < \theta) + ndv] \geq u(\theta) \quad \text{and} \quad H[v(t < \theta) + (n-1)dv] \leq u(\theta), \quad \dot{u}(t) \geq 0 \quad (2-22)$$

or

$$H[v(t < \theta) - ndv] \leq u(\theta) \quad \text{and} \quad H[v(t < \theta) - (n-1)dv] \geq u(\theta), \quad \dot{u}(t) \leq 0 \quad (2-23)$$

Therefore, $v(t)$ can be interpolated as

$$v(t) = H^{-1}[u(t)] = \begin{cases} v(t < \theta) + dv \frac{u(\theta) - H[v(t < \theta) + (n-1)dv]}{H[v(t < \theta) + ndv] - H[v(t < \theta) + (n-1)dv]}, & \dot{u}(t) \geq 0 \\ v(t < \theta) - dv \frac{u(\theta) - H[v(t < \theta) - (n-1)dv]}{H[v(t < \theta) - ndv] - H[v(t < \theta) - (n-1)dv]}, & \dot{u}(t) \leq 0 \end{cases} \quad (2-24)$$

Then, the inverse model is expressed by

$$u(t) = H[v(t)] = H[H^{-1}[u(t)]] = u(t) \quad (2-25)$$

Unlike the Preisach model which inverse is obtained numerically, the Prandtl-Ishlinskii hysteresis model is analytically invertible and therefore can be easily implemented in the hysteresis nonlinearity control system, such as position tracking control [48-49]. The operator, as shown in Fig. 2-7, illustrates the Input-output relation of the classical Prandtl-Ishlinskii hysteresis operator. Suppose that $C_m[0, T]$ is the space of the piecewise monotone continuous functions and the input $u(t) \in C_m[0, T]$ is

monotone on each of the sub-intervals $[t_i, t_{i+1}]$, where $0 = t_0 < t_1 < \dots < t_i < t_{i+1} < \dots < t_N = T$. The output of the classical Prandtl-Ishlinskii model $y(t)$ can be expressed by

$$y(t) = \int_0^R p(r) F_r[u](t) dr \quad (2-26)$$

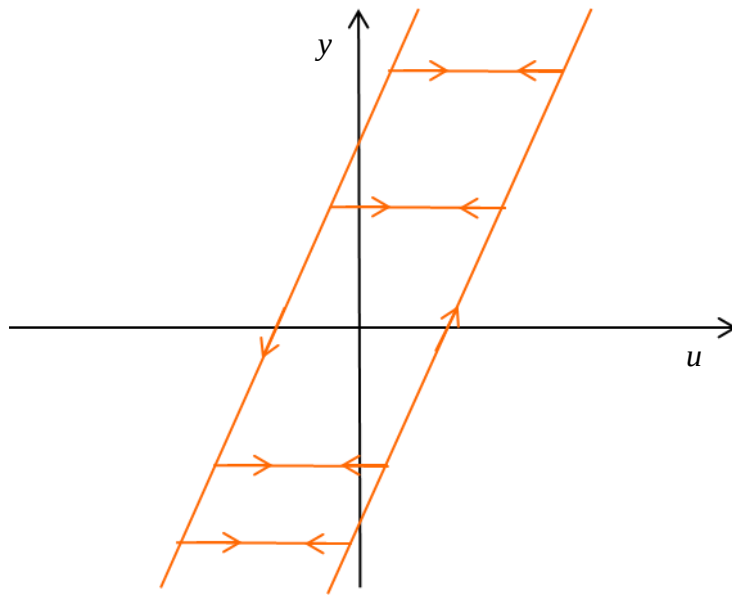


Fig. 2-7 Play hysteresis operator

where $p(r)$ is an inferable positive density function. r is the positive threshold as $0 = r_0 < r_1 < \dots < r_i < r_{i+1} < \dots < r_N = R$. $F_r[u]$ is the classical play hysteresis operator that is analytically expressed for $t_i < t \leq t_{i+1}$ ($i = 0, 1, \dots, N-1$) by

$$\begin{cases} F_r[u](0) = f_r(u(0), 0) = w(0) \\ F_r[u](t) = f_r(u(t), F_r[u](t_i)) \end{cases} \quad (2-27)$$

where $f_r(u, w) = \max\{u - r, \min(u + r, w)\}$.

Even though the Prandtl-Ishlinskii model has been applied to characterize hysteresis

effects of different smart actuators [50-52], the shortcomings of the model (limitation on characterizing the behavior of system with output saturation or asymmetric input-output loops) is eliminated using an alternative generalized play operator [53-54]. As shown in Fig. 2-8, an increase in input v causes the output of the generalized operator z to increase along the curve γ_l , while a decrease in input v causes the output of the generalized operator z to increase along the curve γ_r , resulting in an asymmetric loop. According to Eq. (2-27), the output of the generalized play hysteresis operator is analytically expressed for $t_i < t \leq t_{i+1}$ ($i = 0, 1, \dots, N-1$) as

$$\begin{cases} S_r[u](0) = g_r(u(0), 0) = z(0) \\ S_r[u](t) = g_r(u(t), S_r[u](t_i)) \end{cases} \quad (2-28)$$

here $g_r(u, z) = \max\{\gamma_l(u) - r, \min(\gamma_l(u) + r, z)\}$, The output of the generalized Prandtl-Ishlinskii model, y_g , can be expressed by

$$y_g(t) = \int_0^R p(r) S_r[u](t) dr \quad (2-29)$$

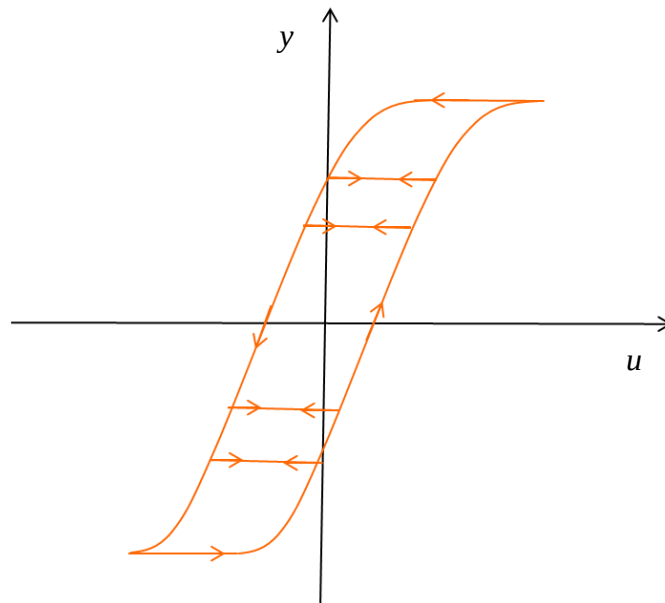


Fig. 2-8 Generalized play hysteresis operator

The inverse model based on the generalized Prandtl-Ishlinskii model is also developed and used as a feedforward compensator for the purpose of mitigating hysteresis nonlinearities of smart materials [55-60]. The output of the generalized Prandtl-Ishlinskii inverse model, $y_{inverse}$, is formulated in discrete form as [61-62]

$$y_{inverse}(k) = \begin{cases} \gamma_l^{-1} \left\{ \frac{1}{p(0)} u(k) + \sum_{j=0}^N \hat{p}_j F_{r_j}^+[u](k) \right\}, & \dot{u} \geq 0 \\ \gamma_l^{-1} \left\{ \frac{1}{p(0)} u(k) + \sum_{j=0}^N \hat{p}_j F_{r_j}^-[u](k) \right\}, & \dot{u} \leq 0 \end{cases} \quad (2-30)$$

$$\hat{p}_j = -\frac{p_j}{(\sum_{i=0}^j p_i)(\sum_{i=0}^{j-1} p_i)}, \quad i = 0, 1, \dots, N-1 \quad (2-31)$$

$$\hat{r}_j = \sum_{i=0}^j p_i (r_j - r_i), \quad j = 0, 1, \dots, N \quad (2-32)$$

2.5.2 Controlling of SMA

In the past, a number of methods had been proposed to control SMA actuators. PID control method is a linear control system that can be used to control SMA actuators.

Asua, Etxebarria and Garcia-Arribas reported that among the linear controllers, PI with anti-windup has the best results for position control of SMA actuators by the experimental results [63]. Da Silva proposed a proportional controller which is applied in active shape control of a flexible beam [64]. Experimental data shows that, in order to eliminate the steady state error for tracking the step signal, the overshoot and actuator saturation is unavoidable. In tuning the gains of PID controller for position control of SMA actuators, for large values of error the proportional gain of the controller should be large enough to produce sufficient control effort for error compensation. On the other hand, for small values of error, a large proportional gain will result in overshoot and

consequently low performance. Popov et al. proposed a PID controller to control the SMA actuator while two methods (the Ziegler-Nichols and internal model control methods) are used to tune the PID controller gains [65]. The simulation results show that the proposed controller is successful in controlling the displacement of the transition point position closer to the trailing edge in order to produce a higher laminar flow region on the airfoil and, therefore, decreases the drag force. Shameli, Alasty and Salaarieh proposed a PID-P3 controller that adds a proportional cubic term to the conventional PID controller [66]. They showed that PID-P3 controllers were more effective than conventional PID controllers for precision position control of a miniature SMA actuator. Since hysteresis effect of SMA actuator is nonlinear system, it is possible to develop nonlinear control system to control it. In the literature, it has been shown that fuzzy logic control is robust in controlling nonlinear systems [67-68]. In the early 1970's, fuzzy control was first introduced in an attempt to design controllers for systems that are structurally complicated to model owing to inherent nonlinearities and other modeling complexities [69]. Cocaud et al. considered fuzzy control of SMA artificial muscles of a 2 DOF robotic arm [70]. Fuzzy PID controllers have shown good accuracy and robustness against system nonlinearities and parametric uncertainties. In addition, PWM controllers are appropriate choices for using as position controllers of SMA actuators in order to reduce the energy consumption by the actuator. Ma and Song showed that using pulse width modulation for control of a SMA actuator effectively saves actuation energy while maintaining the same control accuracy as compared to a conventional PD controller [71]. They showed that PWM demonstrates robustness to the external disturbances. Song and Ma proposed an improved PWM technique called Pulse-Width - Pulse-Frequency (PWPF) modulator which demonstrates that the PD

controller with PWPF modulation consumes 50% less energy than the one without modulation [72]. The biomimetic control of an anthropomorphic artificial finger is presented, which is actuated by three antagonistic SMA muscle pairs that are each configured in a dual spring-biased configuration and it focuses on the design and experimental verification of a new fuzzy pulse-width-modulated proportional-integral-derivative (i.e. fuzzy PWM-PID) controller that is capable of realizing cocontraction of the SMA muscle pairs, as well as online tuning of the PID gains to deal with system nonlinearities and parameter uncertainties [73]. To maintain a desired position of a joint, the corresponding agonistic muscle pairs are cocontracted by the central nervous system and stiffen the joint. Both numerical and experimental results show the performance advantage of the cocontracting fuzzy PWM-PID controller over the original PWM-PID controller.

Furthermore, many researches had worked on nonlinear control aspects of SMA actuators to solve the hysteresis problem in the past. Grant and Hayward demonstrated a variable structure controller which is applied to a pair of antagonist actuators [74]. In this thesis, the feedback switches between the two actuators according to the sign of the displacement error. In addition, a further improvement was added to compensate for known gross nonlinearities by modulating the current magnitude in a discrete manner as a function of the state space position. Therefore, it is possible to realize smooth and robust control with very little cost in complexity. Due to modeling uncertainty, nonlinear behavior of the system and classic control methods such as Proportional-Integral-Derivative control are not able to present fast and accurate performance, a nonlinear robust control algorithm for accurate positioning of a single degree of freedom rotary manipulator actuated by SMA based on Variable Structure

Control is presented [31]. The model includes nonlinear dynamics of the manipulator, a constitutive model of SMA, and electrical and heat transfer behavior of SMA wire. Computer simulation and experimental results for different stabilization and tracking situations are presented and results show fast, accurate, and robust performance of the control system. A gain-scheduled controller for an SMA actuator is presented [75]. A model has been proposed based on concepts from physics in order to achieve accurate control of an SMA actuator which includes Joules heating-convectional cooling to explain the dynamics of temperature, Fermi-Dirac statistics to explain the variation of mole fraction with temperature, and a stress-strain constitutive equation to relate changes in mole fraction and temperature to changes in stress and strain of the SMA. Then, this model is applied to develop a gain-scheduled controller to control the strain in the SMA. Simulation and experimental results show fast and accurate control of the strain in the SMA actuator.

In the second approach of nonlinear controllers, there are many researches focused on the inverse model control system to compensate the hysteresis effect of SMA nonlinear system because of its effectiveness and flexibility. As mentioned above, the inverse models based on the inverse Preisach model [47] or the generalized Prandtl-Ishlinskii model [55-60] are also developed and used as a feedforward compensator of smart materials. Neural networks, which possess properties of nonlinear function mapping and self-adaptation, have been used to model hysteresis and, in some cases, to compensate for hysteresis in SMA actuators [76]. In addition, a neural network inverse model and a sliding-mode based robust feedback controller are used to compensate the SMA hysteresis phenomenon [77]. Since the inverse model was not exact, three more control signals (PD controller, feedforward controller, and sliding-mode base robust

compensator) were modified to improve the control performance in both open-and closed-loop fashions. Moreover, it would not be exact if there was a change of load or working environment because the inverse model was trained offline. Webb and Lagoudas proposed an adaptive hysteresis model for on-line identification and closed-loop compensation because of inaccurate model based on off-line identification [78]. Hysteresis compensation based on the Krasnosel' skii-Pokrovskii hysteresis inverse model is also presented [79]. To alleviate the problem of direct temperature measurements of the SMA wire, an observer based on a simplified thermal model of the SMA wire that requires only rough estimates of the thermal parameters is implemented. The reference input must be sufficiently rich in order to update the parameters of the Krasnosel' skii-Pokrovskii hysteresis model and therefore cannot be used for step regulation tracking.

2.6 Chapter Summary

This chapter provides essential background information on shape memory alloys, including the concept of phase transformation temperature, types of SMA, micro and macro analysis of SMA, modeling and control methods.

Since SMA have many advantages, it is used in commercial or industrial actuator applications. However, there remains obstacles in developing SMA actuators, such as slow speed and the difficulty of accurate position tracking control, as well as energy inefficiency. In order to model and control SMA actuators, many researches had been developed in the past. And they are introduced and summarized in this chapter.

This dissertation aims to provide some groundwork on practical control strategies to

achieve rapid response speed of SMA actuators. Results and significant work that have been accumulated during this Ph.D. research will be documented and described in depth in the following chapters. It is hoped that this thesis will be useful for further research of SMA, including modeling and control of SMA actuators.

CHAPTER 3:

LATENCY DURATION INVESTIGATION OF SMA ACTUATOR

3.1 Introduction

There have been some discussions over the years as to whether shape memory alloys can respond very quickly. As noted in the literature review of chapter 2, researchers have attempted to improve upon the controllable speed of SMA actuators. Some of the results are quite significant, especially in the small or micro-actuator scale [31].

In this chapter, we will investigate the possibility of SMA actuators having very rapid and detectable responses when subjected heating and cooling. The motivations for this investigation of SMA will first be explained. In section 3.3 and 3.4, the method and experimental setup will be described, respectively. The results of the experiments are presented in section 3.5. Some discussions and conclusions about the results are also presented in section 3.6 and 3.7, respectively.

3.2 Motivation and Target

In order to reduce the latency duration, it needs to be investigated. The objectives of the experiments described in this chapter are to determine, firstly, there is hysteresis effect for SMA wire and the cycle time of different heating time with binary control is different, and secondly, if the latency duration exists due to the hysteresis effect. As shown in Fig. 3-1, the output displacement increases from zero to S during heating

processes ac when the temperature increases, and decreases from S to zero during cooling process cf when the temperature decreases. However, the output displacement is unchangeable during the heating process ab and cooling process cd even though the temperature of SMA increases and decreases, respectively. The time T_{ab} (from a to b) and T_{cd} (from c to d) is latency duration of SMA actuator. In this thesis, only the latency duration T_{cd} caused by the nonlinear effect of SMA is investigated. It is useful to find out if the latency duration in an SMA wire can be produced in order to obtain maximum output displacement with binary control. The results of this investigation will be important for SMA control in the following chapters.

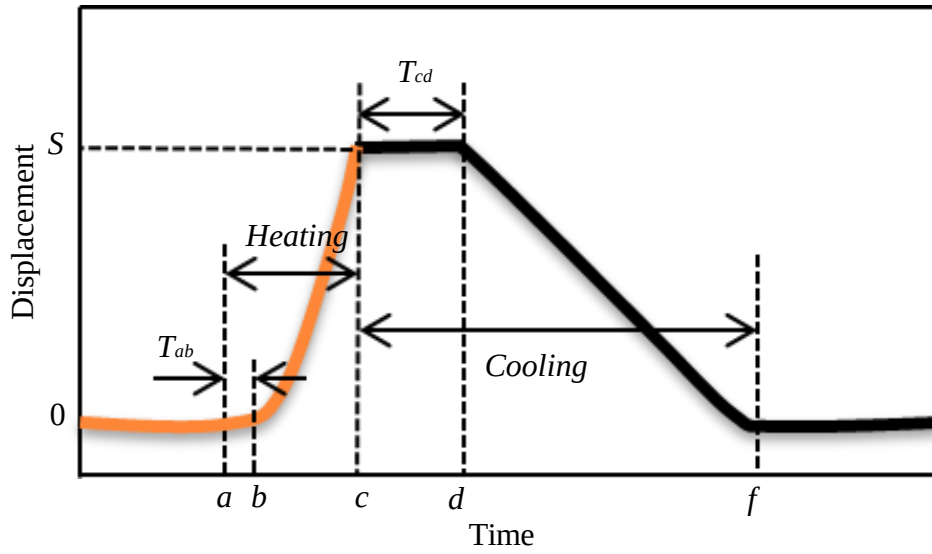


Fig. 3-1 Schematic of output displacement for SMA wire

3.3 Method

Hysteresis and significant nonlinearities in the behavior of SMA actuators encumber effective utilization of these actuators, especially actuators using thick SMA wires which have long latency duration. Instead of controlling temperatures with a Peltier

device, this thesis uses electricity to heat the SMA wires with ‘on-off’ binary control [4]. As shown in Fig. 3-2, Joule resistive heating causes the SMA actuator to output displacement which increases from zero during the heating process ac when power is turned on. The output displacement is steady during ab which is caused by the hysteresis effect in heating process. When power is turned off, the SMA actuator is cooled with natural convection and the output displacement reaches zero at f during the cooling process cf (shown with black line1). Since the output displacement is unchangeable during cd , the latency duration is T_{cd} .

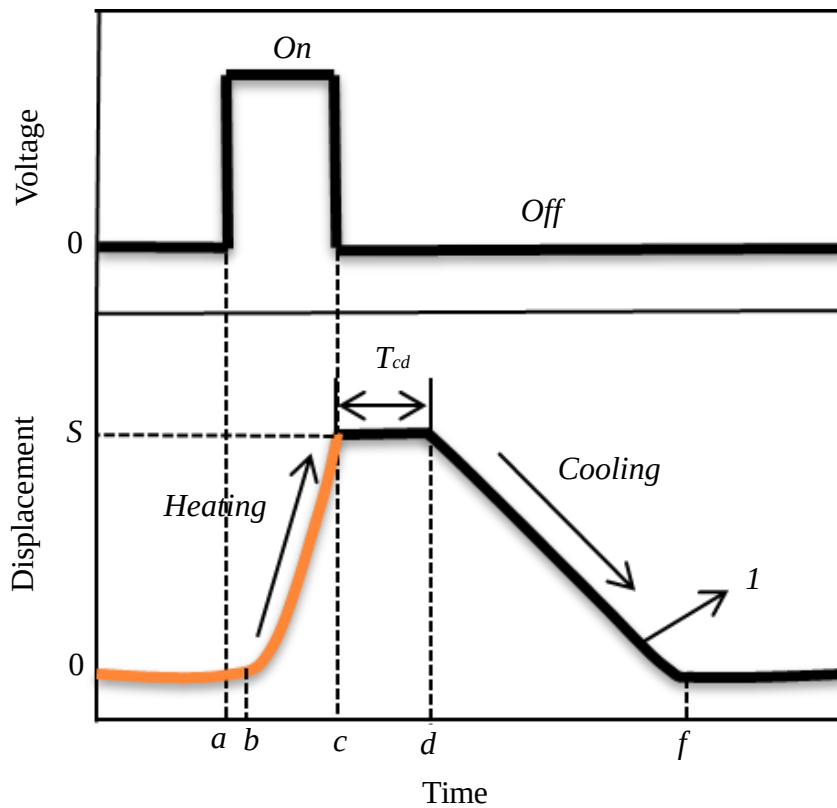


Fig. 3-2 Schematic of the binary control with latency duration T_{cd}

The latency duration caused by hysteresis (T_{ab} and T_{cd} in Fig.3-2) slows both the heating and cooling response speed, especially during the phase transformation of a

thick SMA wire from austenite to martensite. This greatly limits the response of SMA actuators. The heating time is much shorter than the cooling time when the SMA wire is heated by a large heating current.

3.4 Experimental Setup

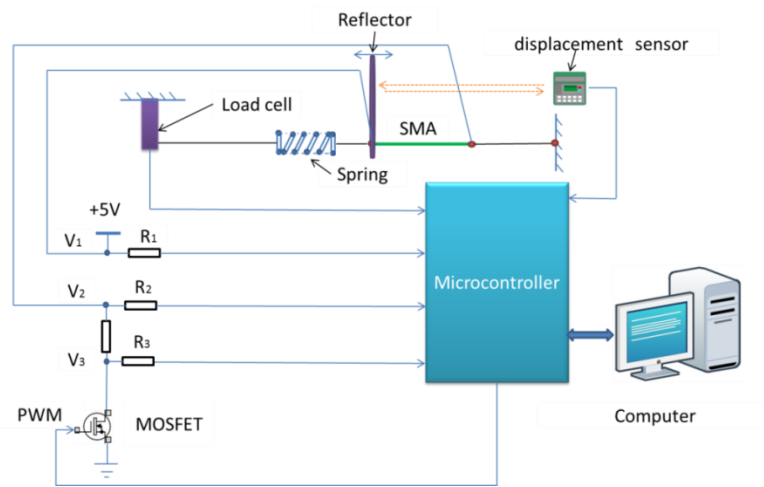


Fig. 3-3 Schematic of experimental setup

In order to obtain the output displacement of SMA wire, the experimental setup is built shown in Fig. 3-3. The fixed end of the wire is connected to a load cell and the other end is attached to a bias spring. When the SMA wire is heated to achieve the austenite length and the electric current is discontinued, the bias spring pulls the SMA wire back to the martensite length. A reflector (reflecting the laser beam) is connected to the spring for displacement measurements. As the SMA wire contracts or extends, the reflector moves forward and backward. Both the data for displacement and force is received by microcontroller, which will be sent to computer. The controller will calculate the output voltage to microcontroller which will transform it to PWM to heat

the SMA wire. 5V is used as the maximum heating voltage to heat the SMA wire. Power resistor is used to protect the microcontroller.

For the experiment, thick SMA wire is selected. As shown in Fig. 3-4(i), two same SMA wires (SMA1 and SMA2, 0.5mm in diameter, 140mm in length) are used in the following tests to obtain the output displacement suffering to different heating time. The latency duration of both SMA wires will be tested separately. Fig. 3-4(ii) shows the length of single SMA wire. As shown in Fig. 3-5, three output voltages are measured for each SMA wire to obtain the variation of resistance. In order to make sure the maximum input current is about 2A which can heat the SMA wire to finish the austenite phase, small resistor (1.1Ω) is added in the driver circuit. The resistance calculation function is denoted by

$$R_{sma} = (v_1 - v_2) / (v_2 - v_3) \quad (3-1)$$

where v_1 , v_2 , and v_3 , are the input voltages which will be used in chapter 4 and chapter 5. More detailed information is listed in Table 3-1.

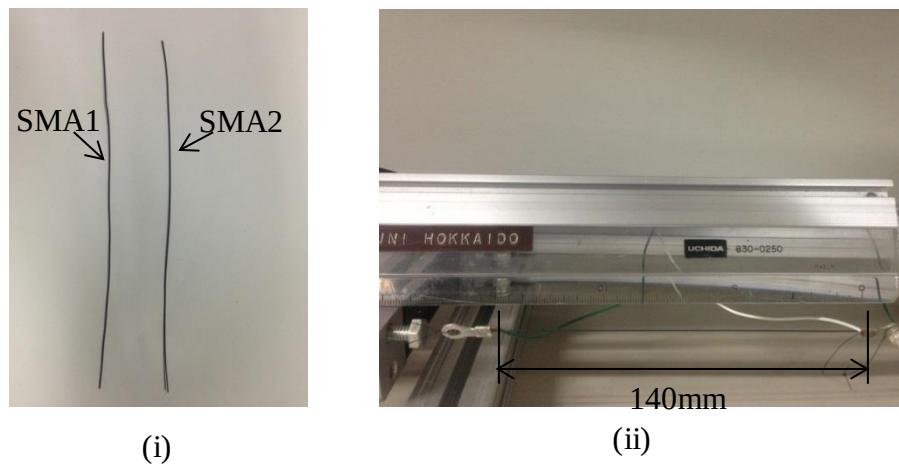


Fig. 3-4 SMA wires used in the experiment

Fig. 3-6 shows the schematic of the experimental setup to test the latency duration with different heating time for SMA wire. In these tests, two SMA wires with the same length are tested. In the following chapters, they will be connected together to verify the proposed method. As shown in Fig. 3-6(i), it is the photo of experimental setup of SMA actuator outlined in Fig. 3-2; Fig. 3-6(ii) is the photo of experimental setup; the displacement and force are obtained by a KEYENCE LC-2000 laser displacement meter and a TEDEA-HUNTLEIGH load cell, respectively.

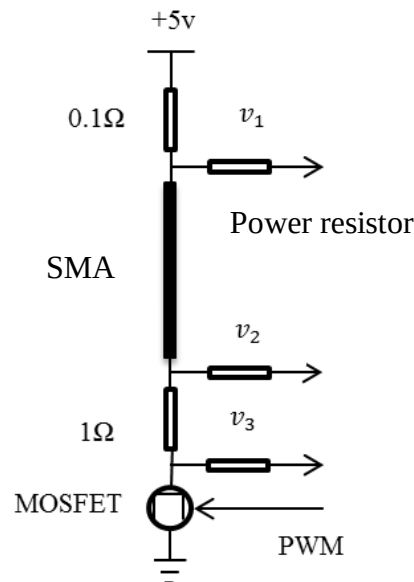


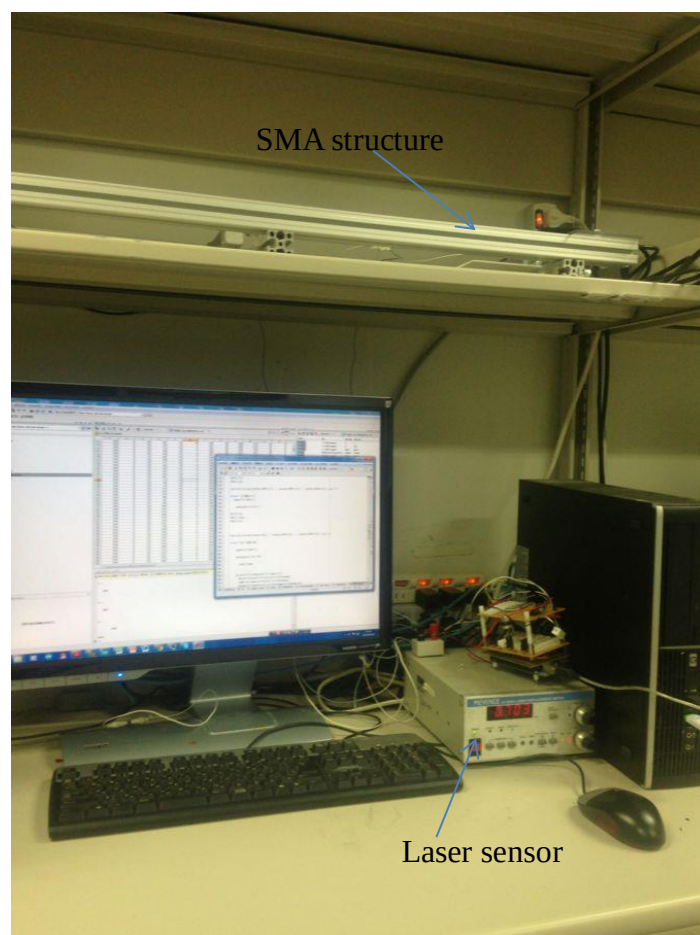
Fig. 3-5 SMA wires used in the experiment

Table 3-1 Parameters for the experiments

Ambient temperature	24°C	SMA diameter	0.5mm
MOSFET	K2232	SMA length	140mm
Power supply	5V	Spring stiffness	653.3N/m
Microcontroller	Arduino	Pretension force	3.27N



(i)



(ii)

Fig. 3-6 (i) Photo of the SMA actuator and (ii) Photo of experimental setup

3.5 Results

3.5.1 Results with Different Ambient Temperature

According to the method mentioned in section 3.3, as shown in Fig. 3-7, ‘on-off’ binary control with 5V is applied to heat the SMA. The SMA is heated from $t_1=5s$ to $t_2=15s$. Fig. 3-8 shows the output displacement with input voltage in Fig. 3-7. It shows that the output displacement is practically unchangeable from $a=5s$ to $b=7.5s$. From b to $c_1=10s$, the output displacement increases from zero to the maximum output displacement 0.81mm during heating process; from c_1 to $c=15s$, the output displacement is practically unchangeable even heated which means the SMA1 is overheated; from c to $d=35s$, the maximum output displacement is 0.9mm when the power is turned off; the SMA starts the transformation from austenite to martensite when output displacement is less than 0.81mm from d . Then, the time $T_{ab}=2.5s$ (from a to b) and $T_{cd}=20s$ (from c to d) is latency duration of SMA actuator.

The martensite start displacement (0.81mm) is 90 percent of the maximum output displacement. When there is no overheating process if the heating time is short, the output displacement will decline to zero during cooling process, and the 90 percent of the maximum output displacement can be used as criteria to decide the martensite start displacement.

Since the temperature of SMA wire is the balance of Joule heat and the heat dissipation to the ambient environment. Therefore, the ambient temperature will affect the heating and cooling time. Fig. 3-9 shows the results of different ambient temperature with input voltage in Fig. 3-7. It clearly shows that the SMA has the similar heating trajectory with different ambient temperature during the heating process from $t_1=5s$ to $t_2=15s$. With the different ambient temperature, the SMA almost finishes the phase

transformation from martensite to austenite at $P=0.81\text{mm}$ during the heating process at 10s; the SMA obtains the same maximum output displacement at $Q =0.90\text{mm}$ during the cooling process as well.

However, compared with other ambient temperature, the SMA extends the fastest when the ambient temperature is 18°C during the cooling process and starts transformation from austenite to martensite at $d_1=31\text{s}$. More detailed information about latency duration with different ambient temperature is listed in Table 3-2.

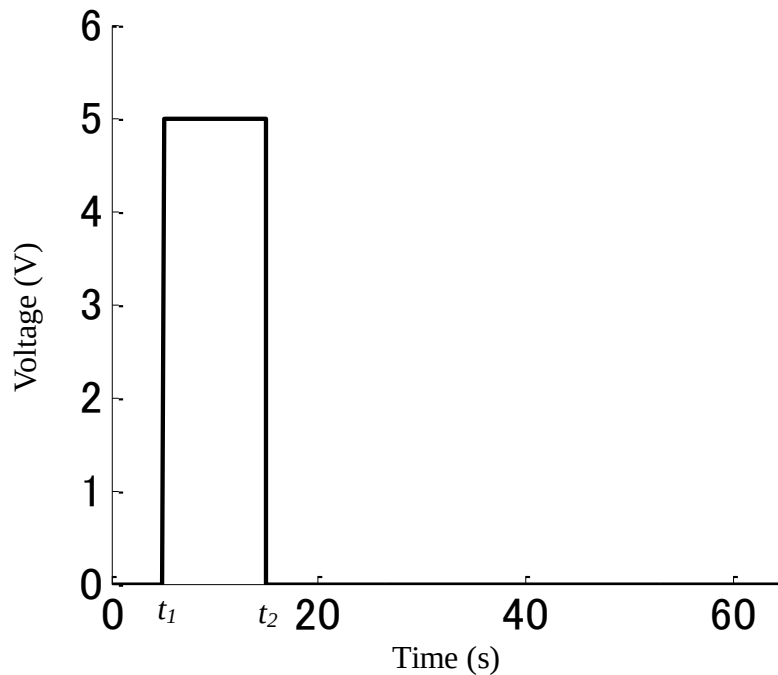


Fig. 3-7 10s as heating time for SMA

Table 3-2 Latency duration with different ambient temperature

Ambient temperature ($^{\circ}\text{C}$)	24	21	18
Latency duration (s)	20	19	16

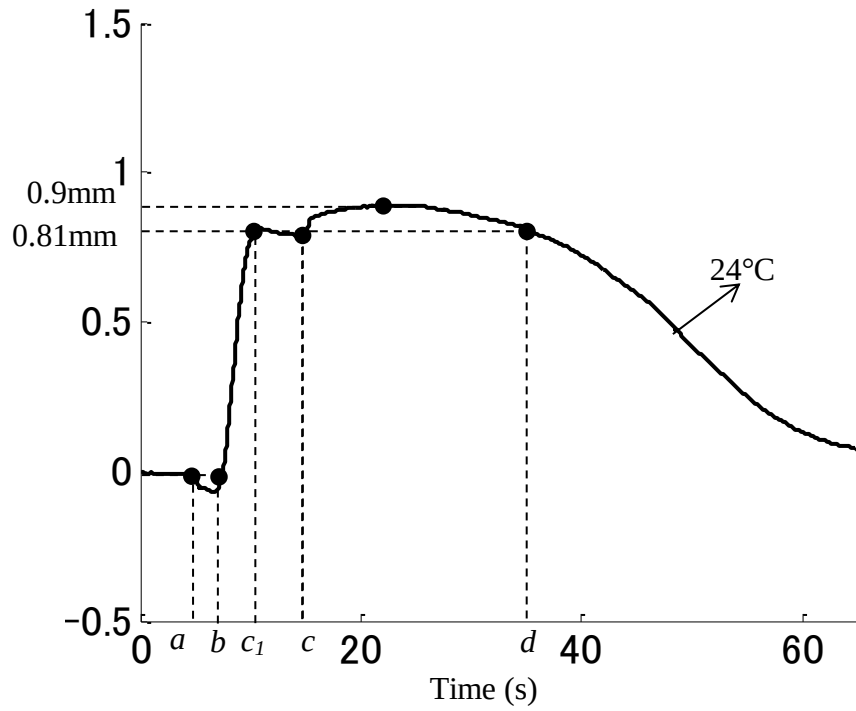


Fig. 3-8 Output displacement for SMA

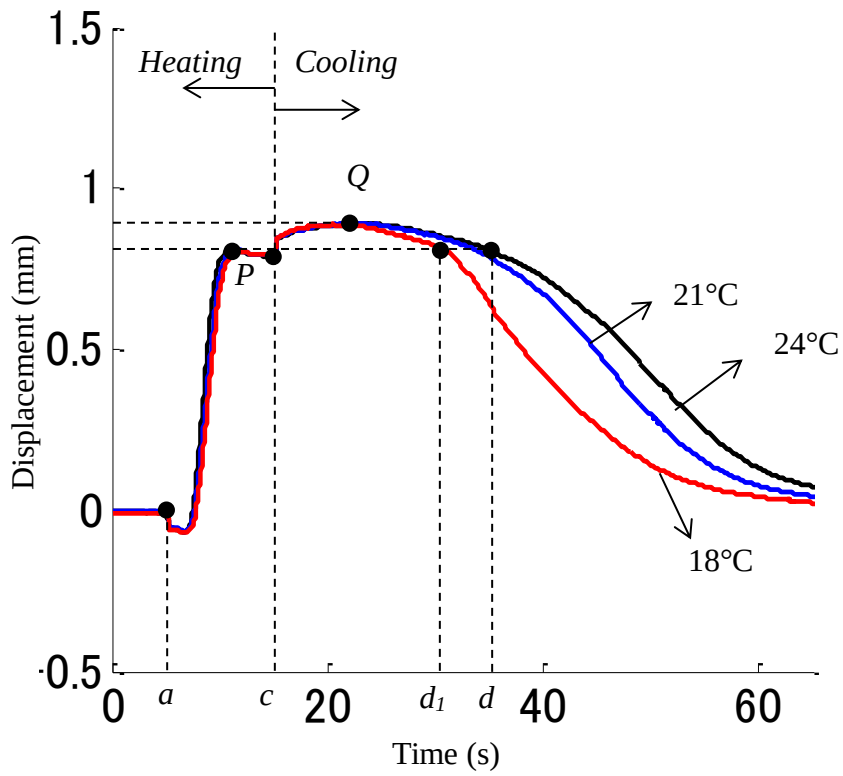


Fig. 3-9 Results with different ambient temperature for SMA

3.5.2 Results with Binary Control

Here, the latency duration and cycle time with different heating time will be investigated for both SMA wires in ambient temperature 24°C in the following experiments. The latency duration of both SMA1 and SMA2 is tested. Fig. 3-10 and Fig. 3-11 show the results of different heating time and output displacement of SMA1, respectively. It is obvious that different heating time leads to different latency duration. As shown in Fig. 3-11, when the heating time is 4s, the maximum output displacement is small, about 0.75mm, and the SMA1 starts transformation from austenite to martensite at $d_1=16.6s$; when the heating time is larger than 5s, such as 7s, the SMA1 will be overheated, and the SMA1 starts transformation from austenite to martensite at $d_2=32s$. More detailed information about latency duration is listed in Table 3-3. As mentioned in section 3.3, the SMA finishes martensite phase when the output displacement reaches zero. Since there are small offset from the position zero when SMA1 finishes the phase transformation from austenite to martensite during the cooling process, a horizontal line along the martensite completion part is used to decide the martensite finish time. According to this criteria, the SMA1 finishes the martensite phase at $f=55s$ when the heating time is 4s.

Table 3-3 Latency duration with different heating time for SMA1

Heating time (s)	10	9	8	7	6	5	4
Latency duration (s)	20	18.6	18. 5	17	16	13	7.6
Maximum Displacement S(mm)	0.9	0.9	0.9	0.9	0.9	0.84	0.75

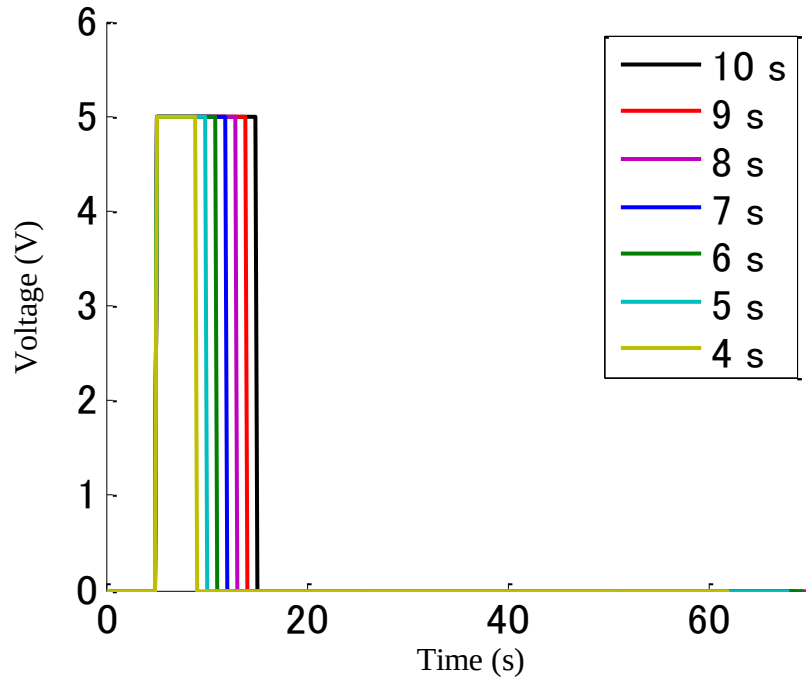


Fig. 3- 10 Heating time of SMA1

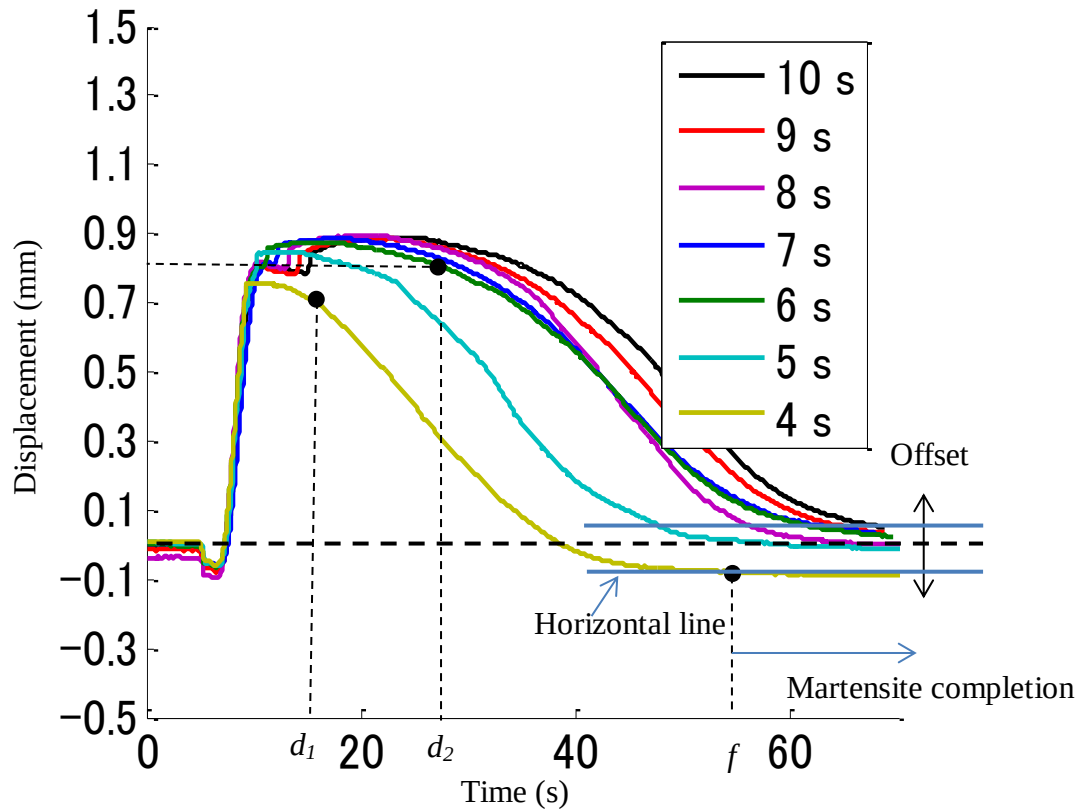


Fig. 3- 11 Output displacement of SMA1

in ambient temperature 24°C

In order to prevent from overheating exactly, the heating time 5s is used to obtain maximum output displacement which is 0.84mm; As shown in Fig. 3-12, the SMA1 starts the phase transformation from austenite to martensite at $d = 23s$ when the martensite start displacement (0.76mm) is 90 percent of the maximum output (0.84mm). Then the SMA1 finishes the cooling process at $f = 60s$. Fig. 3-13 shows the results of output displacement with different heating time for SMA2. It is obvious that different heating time leads to different output displacement as well. Since the maximum output displacement (0.71mm) during the heating process is almost the same as that during the cooling process when SMA2 is overheated, the martensite start displacement can not be decided by percentage of maximum output displacement. Therefore, the latency duration of SMA2 with different heating time, which is overheated or not, is decided by the same criteria (90%) as SMA1.

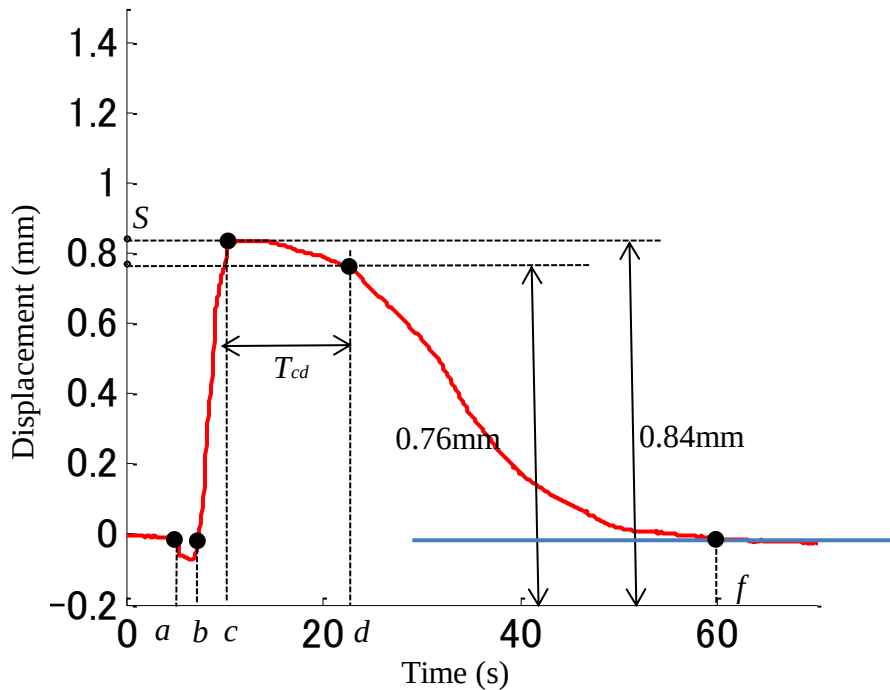


Fig. 3-12 Binary control with latency duration T_{cd} for SMA1
in ambient temperature 24°C

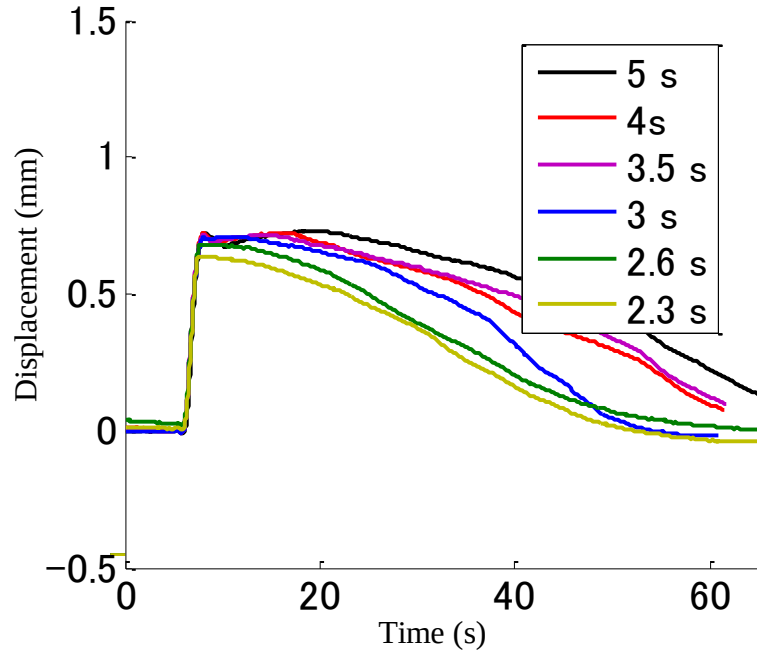


Fig. 3- 13 Output displacement of SMA2
in ambient temperature 24°C

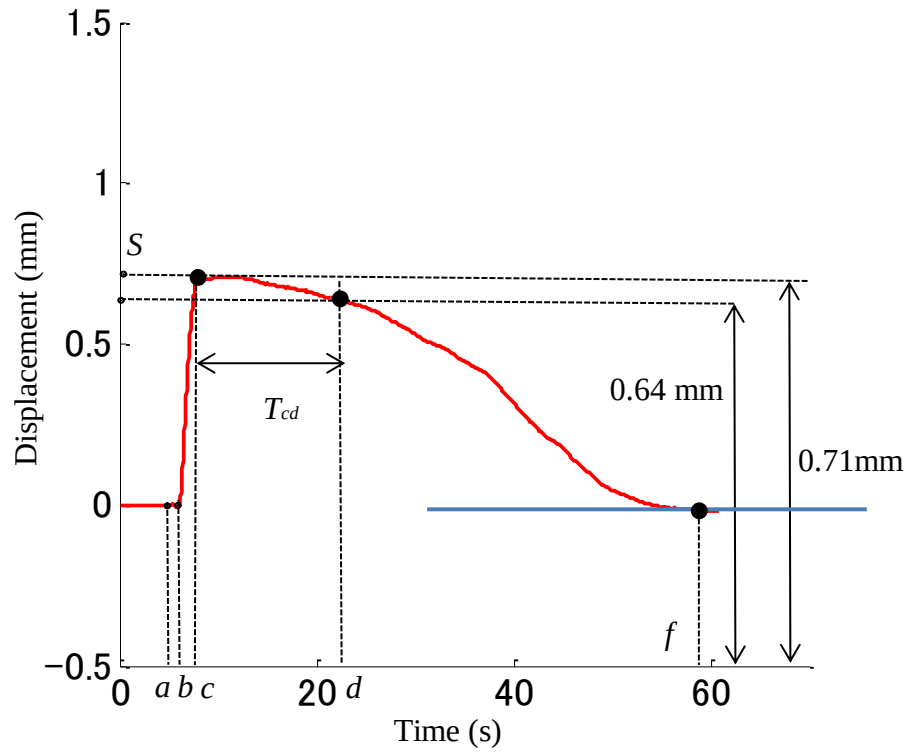


Fig. 3-14 Binary control with latency duration T_{cd} for SMA2
in ambient temperature 24°C

Table 3-4 Latency duration with different heating time for SMA2

Heating time (s)	5	4	3.5	3	2.6	2.3
Latency duration (s)	23	15.5	16	14	10.7	9.9
Maximum Displacement $S(\text{mm})$	0.71	0.71	0.71	0.71	0.68	0.64

Fig. 3-13 also shows that when the heating time is 5s, the SMA wire will be overheated which leads to take longer time to decline when the power is turned off. In order to prevent overheating exactly, the heating time is set 3s to obtain maximum output displacement $S = 0.71\text{mm}$ for SMA2; when the heating time is 2.3s, the output displacement is about 0.64mm. More detailed information is listed in Table 3-4.

Fig. 3-14 shows results of the latency duration with heating time 3s for SMA2. The SMA2 completes the phase transformation from austenite martensite during heating process ac . And SMA2 completes the phase transformation from martensite to austenite during cooling process cf . According to the criteria mentioned above, the martensite start displacement is 0.64mm. The SMA2 starts the martensite phase at $d=22\text{s}$ and finishes the cooling process at $f=59\text{s}$. Comparison about the latency duration corresponding to Fig. 3-1 is listed in Table 3-5.

Table 3-5 Heating time and cycle time of SMA wires

	T_{ab}	T_{bc}	T_{cd}	T_{df}	Cycle time
SMA1	1.8s	3.2s	13s	36s	54s
SMA2	1.7s	1.3s	14s	37s	55s

3.6 Consideration and Discussion

The prototype system developed for the experimental investigation of latency duration has demonstrated the feasibility. There are, however, a few critical points needing further consideration.

1. As shown in Fig. 3-8, the output displacement slightly changes from a to b and the minimum output displacement is -0.08mm . In addition, the output displacement slightly decreases from c_1 to c when heated. The reason is when the temperature of SMA increases, the SMA will expand due to the function that metals expand when heated and contract when cooled. When the temperature of SMA is larger than austenite start temperature from b , and when the temperature of SMA is lower than austenite finish temperature from b to c_1 , there will be output displacement caused by the shape memory effect. Compared with the output displacement caused by shape memory effect, the displacement caused by thermal expansion can be ignored during bc_1 . Moreover, the output displacement slightly increases and the maximum output displacement is 0.9mm during cooling process cd . The reason is when the temperature of SMA decreases, the SMA will contract due to the function that metals expand when heated and contract when cooled. When the temperature of SMA is lower than martensite start temperature from d , there will be output displacement caused by the shape memory effect and the displacement caused by thermal contraction can be ignored.
2. As shown in Fig. 3-9, the output displacement is almost the same with different ambient temperature during the heating process from 5s to 15s. Because heating voltage is large enough to make the SMA wire finish the phase transformation

from martensite to austenite for each test. And the heat loss with different ambient environment can be ignored during heating process. However, the output displacement decreases the fastest when the ambient temperature is 18°C, because the heat loss in 18°C from the SMA to ambient environment is faster than in 22°C and 24°C. As shown in Table 3-2, the difference of latency duration and cooling time for different ambient temperature is caused by different heat loss rate in air [38]. Therefore, in order to obtain correct latency duration, the ambient temperature should be steady.

3. As shown in Fig. 3-11 and Table 3-5, the latency duration with heating time 10s (overheated) is 20s which is larger than that with heating time 5s (13s). It takes much longer time to decline during the cooling process once the SMA is overheated. Therefore, in order to obtain rapid response speed for SMA actuator, it is important to control the heating time to avoid overheating.
4. As shown in Fig. 3-12 and Table 3-5, since the heating voltage is large, the latency duration T_{ab} during the heating process is much smaller compared with latency duration T_{cd} . If the heating voltage is small, the latency duration T_{ab} will be more obviously. As shown in Fig. 3-15, latency duration T_{ab} for input voltage 2.94 V is 4.2s which is larger than with input voltage 5V (1.8s) because the temperature of SMA increases slower. And, there will be no output displacement when the input voltage is small, such as 1V because the temperature is less than martensite start temperature. It is possible to shorten the latency duration T_{ab} with more segments, such as 4 SMA wires connected together.
5. As shown in Fig.3-12, Fig.3-14, and Table 3-5, due to the specimen error in length and material, there are small differences about the maximum output

displacement (0.84mm for SMA1 and 0.71mm for SMA2) and latency duration (13s for SMA1 and 14s for SMA2) even though the SMA wires are tested in same ambient temperature.

6. Fig. 3-16 shows the results with thin SMA wire (0.15mm in diameter) and thick SMA wire (0.5mm in diameter) with the same maximum output displacement (0.56mm) and 140mm in length with ambient temperature 21°C, the SMA finishes the heating process at *c* and starts the martensite phase at *d*. Then the latency durations for both SMA wires are 0.5s and 2s. The output displacement of both wires reaches zero at 20s and 55s during the cooling process when the power is turned off, respectively. It clearly shows that the thick SMA wire has longer latency duration and slower cooling response speed, because it has slower heat loss ratio than thin one.

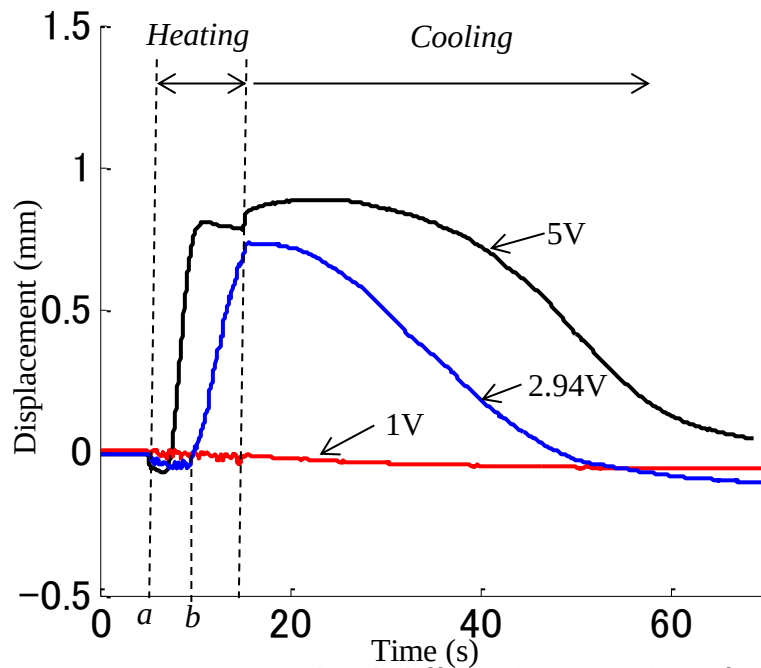


Fig. 3-15 Binary control with different heating voltage for SMA1 in ambient temperature 24°C

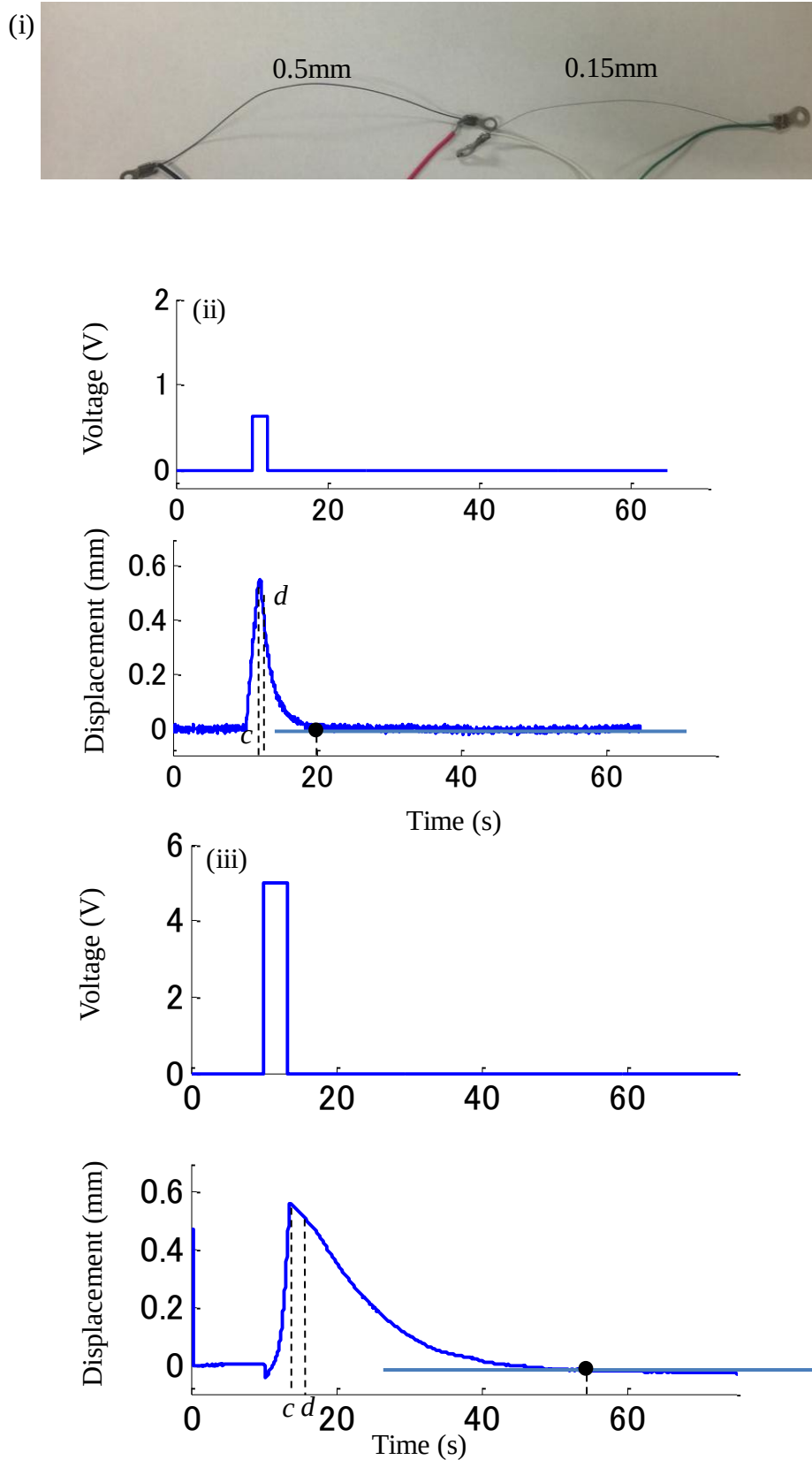


Fig. 3-16 (i) SMA wires; (ii) Results for SMA 0.15mm in diameter; (iii) Results for SMA 0.5mm in diameter in ambient temperature 21°C

3.7 Chapter Summary

The experimental results show that there is hysteresis effect in SMA wire. Due to the hysteresis effect, it is reasonable to test the latency duration caused by the hysteresis effect with the binary control.

It has been demonstrated in this chapter that the designed experimental setup can meet the need of demand to detect the displacement and a 0.5mm diameter NiTi SMA wire have rapid and detectable responses during the heating process when applied 5V compared with the cooling process.

Experiments not only indicate the existence of the latency duration at room temperature which is arisen from the hysteresis effect of SMA wire, but also the variation of it with different heating time. As shown in Table 3-5, with the proper heating time to obtain the maximum output displacement and eliminate the overheating, the latency duration is about 24.1% and 25.4% of cycle time for SMA1 and SMA2, respectively. We have observed there is small difference between two SMA wires such as the maximum output displacement.

These observed results are very important to the work in the following chapters. Based on the results, it is proposed that some new control method may be capable of improving the speed of response by shortening the latency duration during the cooling process.

CHAPTER 4:

PHASE RESISTANCE FEEDBACK CONTROL TO ACHIEVE RAPID RESPONSE SPEED

4.1 Introduction

Although SMA appears to be attractive for robot applications, they also come with several limitations. First, since their operating principle is based on a phase transition in a metal, they have highly nonlinear properties such as the stress-strain relationship, internal resistance, latent heat of transformation, and thermal conductivity are all phase dependent. Second, their input-output relations contain a wide hysteresis loop, making them difficult to control accurately. The third major limitation of SMA is efficiency. The energy efficiency of SMA is theoretically restricted to approximately 10%. Efficiency is often less than 1% in practical applications, since the driving principle of the actuator can be considered as a heat engine operating at low temperatures. Hence, applications of SMA actuators must be directed at areas where energy efficiency is not a concern. SMA also have two major inherent mechanical limitations: limited percent strain and low bandwidth. The absolute percent strain is approximately 8%. With practical applications restricted to around 5%. The motion bandwidth of SMA actuator is generally low.

Many research had focused on improving the response speed of the SMA, including antagonistic-pair arrangements [80], variable structures [74], and two-stage relay control [37]. Thin SMA wires, thinner than 0.2mm, can achieve the aim as actuators because the cooling speed is fast in air. Thick SMA wires, thicker than 0.5mm, have

long latency durations, making it difficult to obtain rapid response speeds. Some researchers have shown that active cooling chips [4, 81] and variable structure control can improve reaction times of SMA actuators [74] (Fig. 4-1). As a function of temperature, SMA changes the shape through a metallographic transformation that results in resistance changes. The relationship between electrical resistance and displacement of the SMA has been investigated [13]. Resistance also can be used as feedback in the control system of SMA actuator. SMA actuators are chosen as an example of a plant with hysteresis and a control system to compensate the hysteresis is proposed controlling the electrical resistance of SMA, which reflects its state, and the usefulness of the controller is confirmed experimentally [82].

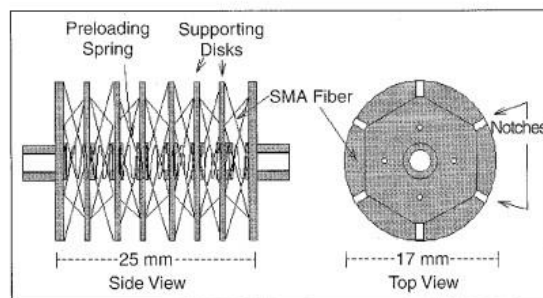


Fig. 1. Shape memory alloy actuator.

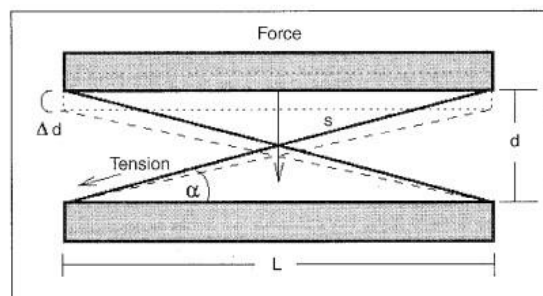


Fig. 2. Simplified case: two beams with two fibers.

Fig. 4-1 An illustration of variable structure control [74]

In chapter 3, the latency duration of SMA wire is investigated. In this chapter, we will investigate the possibility of SMA actuators having rapid response when using phase resistance as feedback to shorten the latency duration. The motivations will first be explained. In section 4.3 and 4.4, the method and results will be described, respectively. Some discussions and conclusions about the results are also presented in section 4.5 and 4.6, respectively.

4.2 Motivation and Target

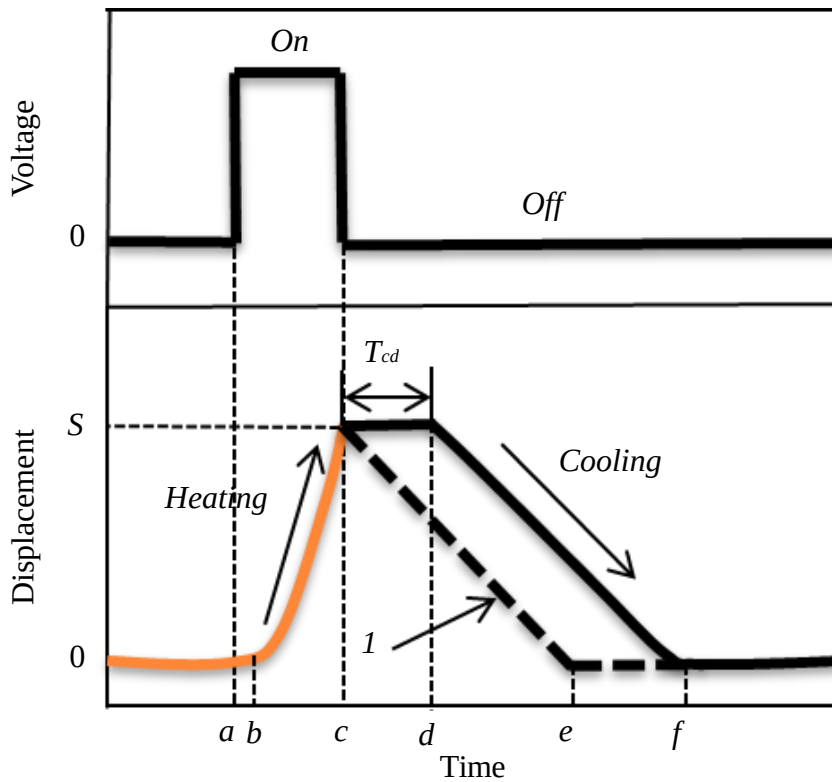


Fig. 4-2 Schematic of the binary control with latency duration T_{cd}

To obtain rapid response speed for SMA actuator, an alternative approach, PRFC (Phase resistance feedback control), is proposed to control the phase resistance in a closed-loop feedback system of two connected thick SMA wires. There are two basic

concepts underlying the PRFC. One is the introduction of phase resistances which divide the hysteresis loop into four parts. The other is to utilize the phase resistances as the feedback to reduce the latency duration. Experiments to prove the effectiveness demonstrated that the latency duration caused by the hysteresis effect was shortened and showed the advantages of the proposed method. Experimental results that demonstrate the advantages and justify the concepts are also presented. As discussed in chapter 3, the traditional control method for position is an ‘on-off’ binary control. As shown in Fig. 4-2, T_{cd} is the latency duration which has been investigated in chapter 3. Here, PRFC is proposed to achieve rapid response speeds, like the dotted line 1 (Fig. 4-2). The Joule resistive heating causes the SMA actuator to contract during the heating process ac when power is turned on. The SMA actuator is cooled with natural convection which extends from c and completes the cooling process at e , shortening the latency time T_{cd} .

4.3 Method

4.3.1 Phase Resistance

The SMA may be seen as a smart material that changes shape due to changes in temperature. These changes are reversible. The shape memory effect arises from temperature and stress dependent shifts in the crystalline structure of the SMA, shifts between martensite and austenite phases. During the phase transformation processes, the resistance changes with changes in temperature. As with the strain-to-temperature or resistance-to-temperature relationship, the strain-to-resistance curve exhibits a hysteresis loop [83-85]. As shown in Fig. 4-3 and Table 4-1, there are four phase transformation resistances R_{as} , R_{af} , R_{ms} , and R_{mf} . In the heating process, from A to B , the resistance increases from R_{mf} to R_{as} without changes in the output strain; from B to C ,

the resistance decreases from R_{as} to R_{af} as the SMA transforms from martensite to austenite. In the cooling process, from C to D , the resistance decreases from R_{af} to R_{ms} without changes in the output strain, while from D to A , the resistance increases from R_{ms} to R_{mf} as the SMA transforms from austenite to martensite.

Table 4-1 List of important data in Fig. 4-3

R_{as}	Austenite start resistance
R_{af}	Austenite finish resistance
R_{ms}	Martensite start resistance
R_{mf}	Martensite finish resistance
T_{ab}	Heating time from A to B
T_{bc}	Heating time from B to C
T_{cd}	Cooling time from C to D
T_{df}	Cooling time from D to A

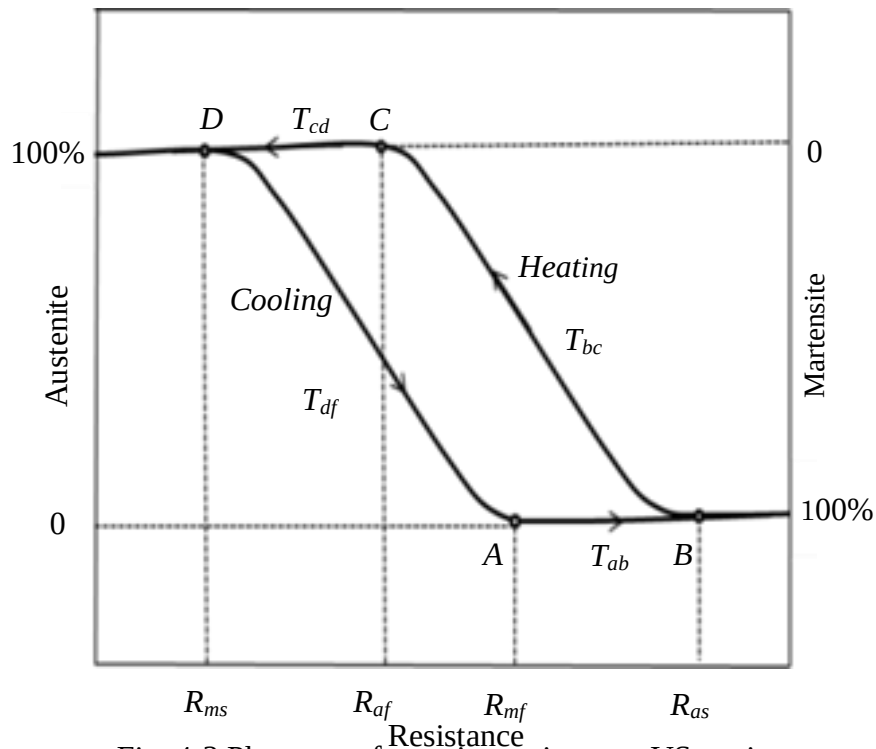


Fig. 4-3 Phase transformation resistances VS strain

4.3.2 Phase Resistance Feedback Control Method (PRFC)

As shown in Fig. 4-3, we have divided the heating and cooling process into four parts with times T_{ab} , T_{bc} , T_{cd} , and T_{df} , as listed in Table 4-1, and a cycle time T is defined as

$$T = T_{ab} + T_{bc} + T_{cd} + T_{df} \quad (4-1)$$

The SMA shrinks during the time T_{bc} rather than T_{ab} in the heating process and extends during the time T_{df} rather than T_{cd} in the cooling process. If the gap between the heating and cooling lines (Fig. 4-3) is large, then the resistance-phase state characteristics of SMA have strong hysteresis properties. In this case it is simple to identify phase resistances.

The critical aspect of the PRFC method is to shorten the total cooling time by controlling the phase resistances with two connected SMA wires (SMA1 and SMA2 in Fig. 3-4) that are coordinated. Fig. 4-4 shows the basic theory behind this method, using the definitions in Table 4-1, and may be explained as follows.

As shown in Fig. 4-4(i), in section AC, the resistance of SMA1 is maintained at R_{ms} , and there is no displacement output from the SMA1 wire. The resistance of SMA2 increases from R_{mf} to R_{as} and then decreases to R_{af} . The SMA2 wire completes the phase transformation from martensite to austenite. As shown in Fig. 4-4(ii), the SMA2 elongates and then contracts, which respectively leads to positive and negative displacements during the heating process AC; the maximum output displacement is at S. The heating time T_h can be described by

$$T_h = T_{AB} + T_{BC} = T_{ab} + T_{bc} \quad (4-2)$$

In section CD, once the resistance of SMA2 reaches R_{af} , the SMA1 is rapidly cooled without any current and the resistance of SMA2 is maintained at R_{ms} . The result is that there is no displacement output from the SMA2 wire. The resistance of SMA1 increases

to R_{mf} and the SMA1 wire completes the phase transformation from austenite to martensite. During the cooling process, CD , the displacement of SMA1 is positive. The cooling time T_c can be given as follows

$$T_c = T_{CD} = T_{df} \quad (4-3)$$

In addition, the time of a cycle for one SMA wire T_{single} is longer than with the binary control method. It is expressed as follows

$$T_{single} = T_{ab} + T_{bc} + T_{CE} + T_{df} \quad (4-4)$$

where $T_{CE} > T_{cd}$

Combining the two SMA wires, the latency time T_{cd} can be eliminated. Therefore the time of a cycle in PRFC, T_p , is given as

$$T_p = T_h + T_c = T_{ab} + T_{bc} + T_{df} \quad (4-5)$$

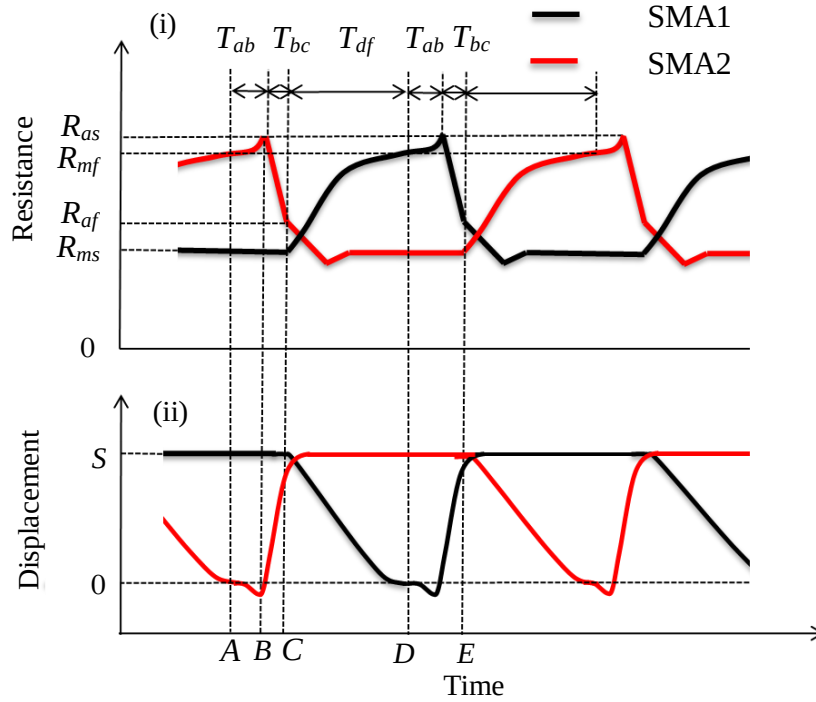


Fig. 4-4 Schematic for the PRFC method

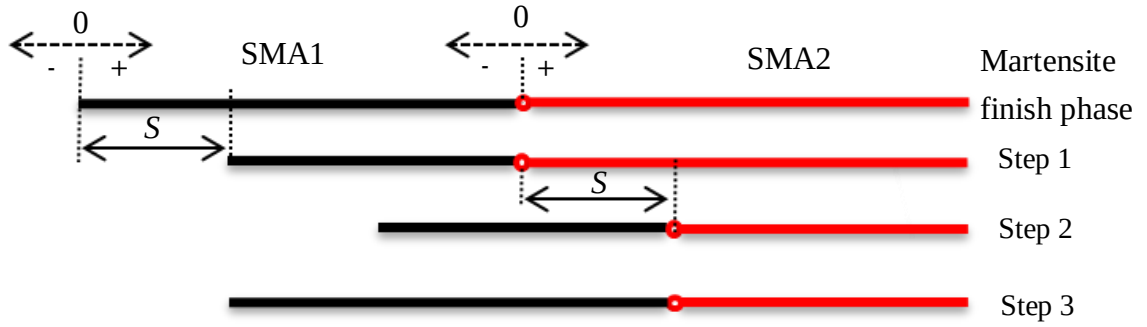


Fig. 4-5 Output displacement with the PRFC

To explain the PRFC method in more detail, the output displacement of SMA actuator is demonstrated. As shown in Fig. 4-5, the displacement is zero when both SMA wires are in the martensite phase before the PRFC.

Step 1: at the beginning of PRFC, SMA1 is in the martensite starting phase and SMA2 is in the martensite finishing phase, the output displacement is S .

Step 2: SMA1 is in the martensite starting phase and SMA2 completes the transformation from martensite to austenite, the output displacement is S as well.

Step 3: once the SMA2 completes the transformation from martensite to austenite, SMA1 starts the transformation from austenite to martensite. At the same time, SMA2 remains at martensite starting phase, the output displacement is S ; Combining the two SMA wires, T_{cd} is shortened and the maximum output displacement from step 1 to step 3 is S .

4.3.3 PID controller

The phase resistance R_{ms} needs to be used as feedback to maintain the output displacement precisely by tuning the PID parameters. A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an "error" value as

the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs. The PID controller calculation algorithm involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D, these values can be interpreted in terms of time. P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, a damper, or the power supplied to a heating element. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the setpoint, and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability. To be able to use the phase resistances as feedback, a PID controller was installed instead of the traditional ‘on-off’ binary control, and this is shown in Fig. 4-6. The parameters of the PID controller are based on the value of the error e . The PWM value is then converted to voltage and heats. Since the microcontroller can only receive the value from 0 to 255, then the output of PID controller is converted to this range. The output voltage is from 0 to 5V, and the following equations represent the error output voltage relationship.

$$Pid = K_p * e(t) + K_i * \int_0^t e(t)dt + K_d * \frac{de(t)}{dt}, \quad Pid \in [-255, \quad 0] \quad (4-6)$$

where $e(t)$ is the signal error of the resistance.

$$V_{output} = -5 * Pid / 255 \quad (4-7)$$

There are two purposes of using resistance as feedback.

1. It can maintain the output displacement without using displacement as feedback.
2. The SMA wire is ready to cool down quickly without duration during the cooling process since the latency duration is shortened.

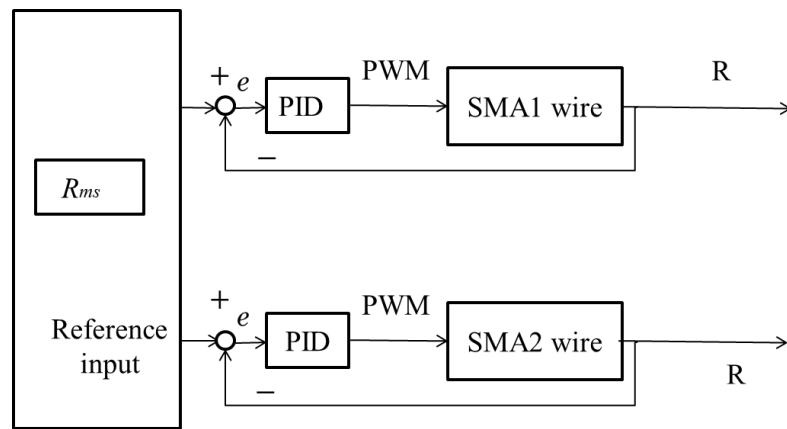


Fig. 4-6 Block diagram of PRFC

4.3.4 Experimental Setup

An experimental setup of the proposed double SMA actuator was made, and as shown in Fig. 4-7(i), SMA wires are connected by an insulation joint to prevent short circuiting; the fixed end of the wire at the joint is connected to a load cell and the other is attached to a bias spring. A reflector is connected to the spring for displacement measurements. As the SMA wire shrinks and extends, the reflection sheet moves forward and backward. Fig. 4-7(ii) is the experimental setup explained in Fig. 4-7(i). Detailed parameters of the experiment are shown in Table 3-1.

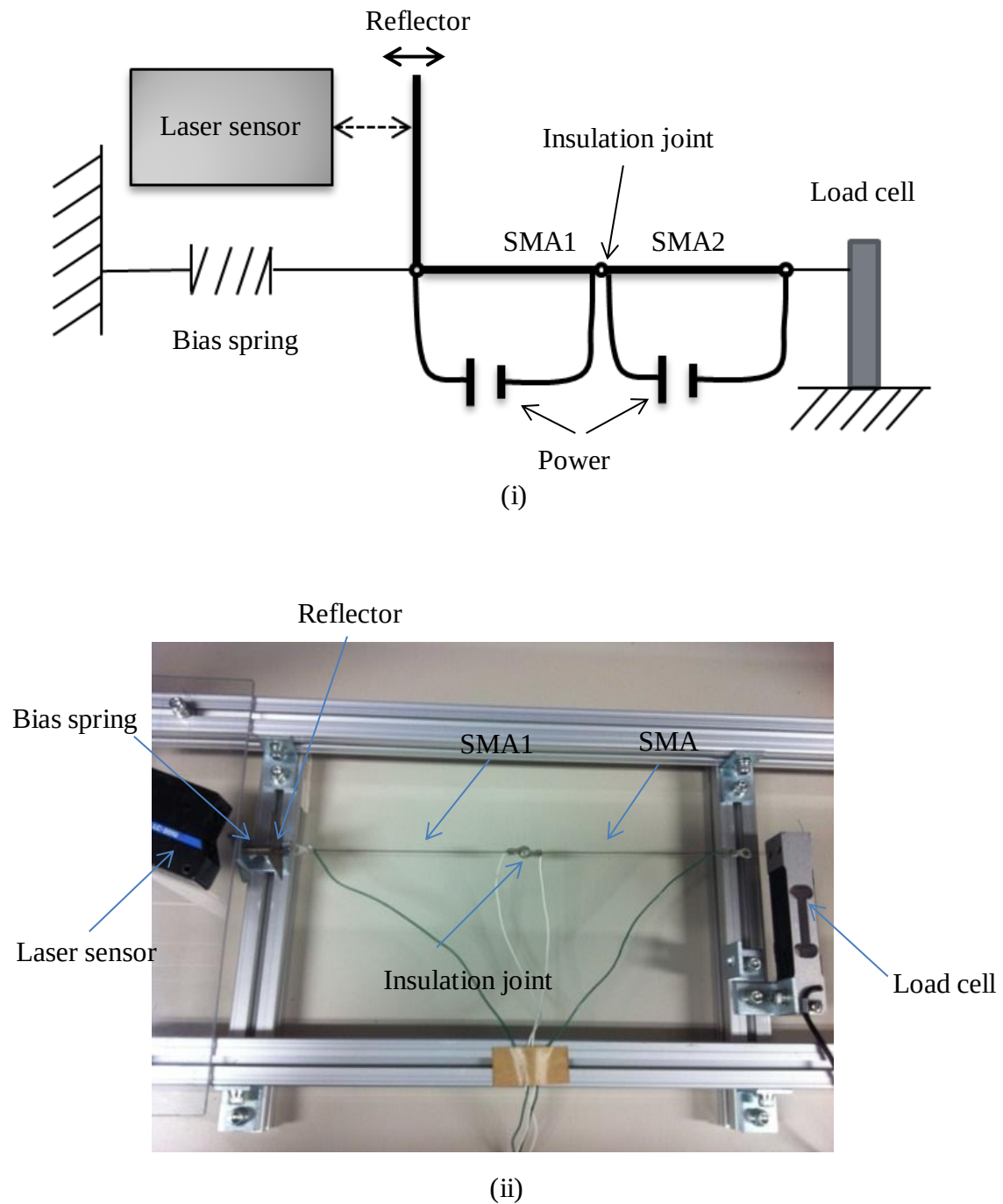


Fig. 4-7(i) Schematic outline of the experimental setup and (ii) Photo of the experimental setup

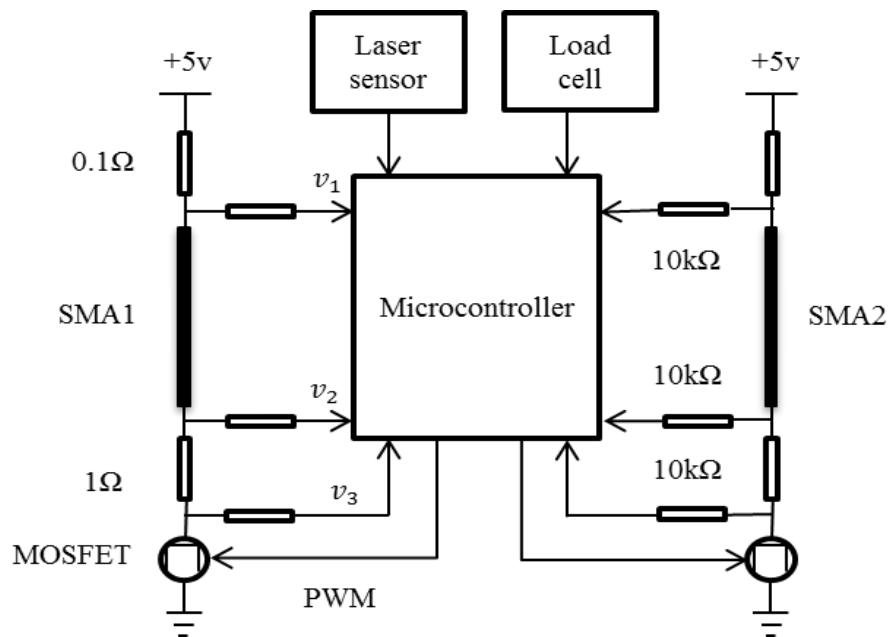


Fig. 4-8 Driver circuit

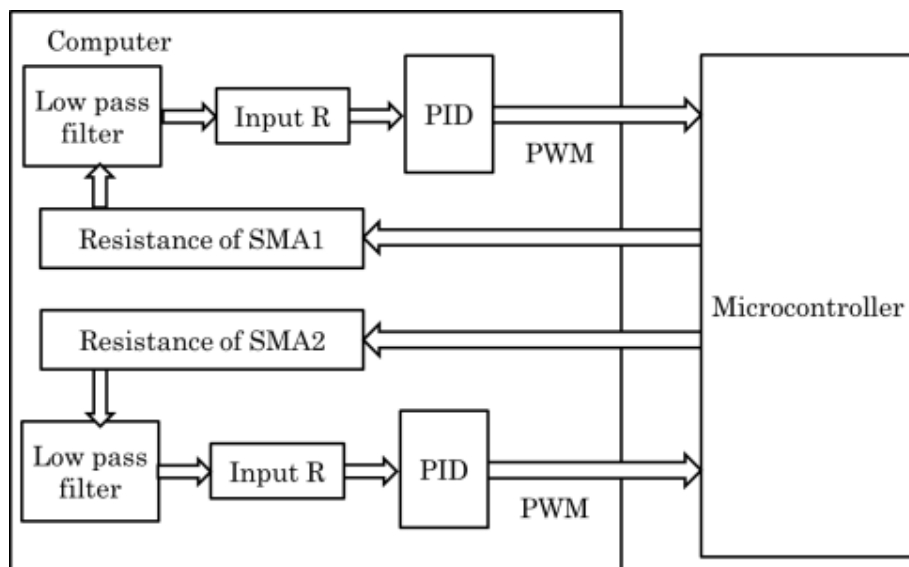


Fig. 4-9 Control loop of the experiment

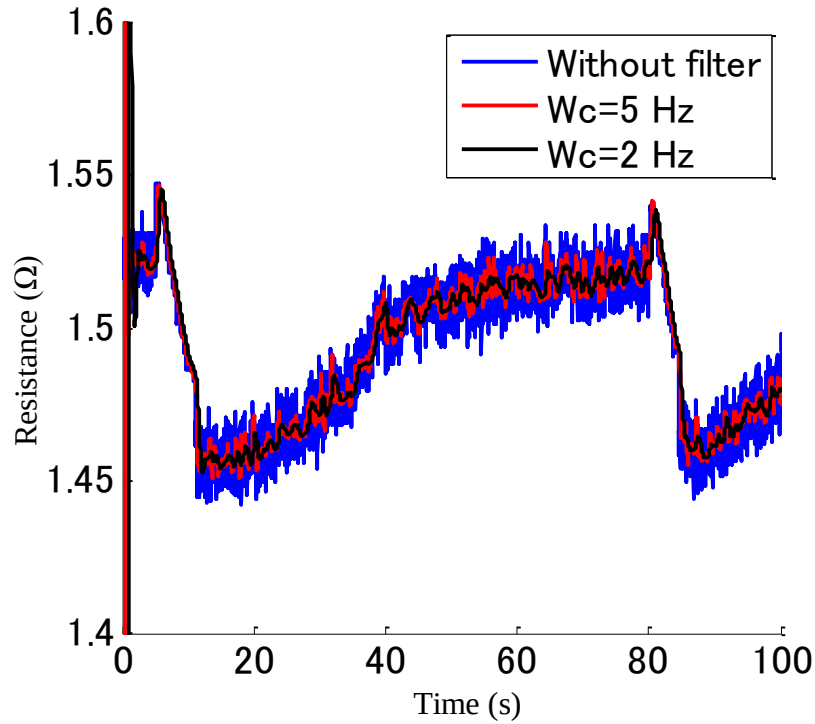


Fig. 4-10 Results with different cut-off frequency for SMA1 and SMA2
in ambient temperature 24°C

In order to measure the resistance of both SMA wires, the driver circuit is designed shown in Fig. 4-8. Two SMA wires are measured and the calculation equation can be expressed by Eq. (3-1) in chapter 3. The displacement is detected as the same in chapter 3 by microcontroller. As shown in Fig. 4-9, a computer is connected to a microcontroller with a USB port. The microcontroller sends data used as the feedback to the computer and receives the control values sent by the computer. Then, the microcontroller sends a PWM value to the driver circuit to control the input voltage of the SMA wires. Before identify the phase resistance, we need to filter the data obtained from microcontroller. The sampling time is 0.05s, and to filter out the high-frequency noise component, a third order Butterworth filter with a cut-off frequency. Fig. 4-10 shows the results with different cut-off frequency and $W_c=2\text{Hz}$ is used in the experiment.

4.4 Results

4.4.1 Phase Resistance Identification

To identify phase transformation resistances, it is necessary to determine the major hysteresis loop of the displacement-to-resistance of SMA wires involved, and it is also important to determine the heating time, especially to prevent overheating.

In chapter 3, the heating time 5s is used to heat the SMA wire to obtain maximum output displacement instead of overheating. Fig. 4-11 shows the results of resistance with heating time 5s in binary control for SMA1. It obviously shows that the resistance will increase first and then decrease during the heating process. When the power is turned off, the resistance increases from $t_3=10s$ during the cooling process. Fig. 4-12 shows results of resistance with heating time 3s in binary control for SMA2 and the resistance increases from $t_3=8s$ during the cooling process. It obviously shows the same results as SMA1. Therefore, the hysteresis loop with heating time 5s and 3s are used as major hysteresis loop to identify the phase resistance of SMA1 and SMA2, respectively.

Table 4- 2 Transformation resistances parameters

Resistances of SMA1	R_{as}	1.535 Ω	Resistances of SMA2	R_{as}	1.445 Ω
	R_{af}	1.480 Ω		R_{af}	1.390 Ω
	R_{ms}	1.470 Ω		R_{ms}	1.360 Ω
	R_{mf}	1.515 Ω		R_{mf}	1.413 Ω
Displacement of SMA1	Max	0.84mm	Displacement of SMA2	Max	0.71mm
	Min	-0.08mm		Min	-0.02mm

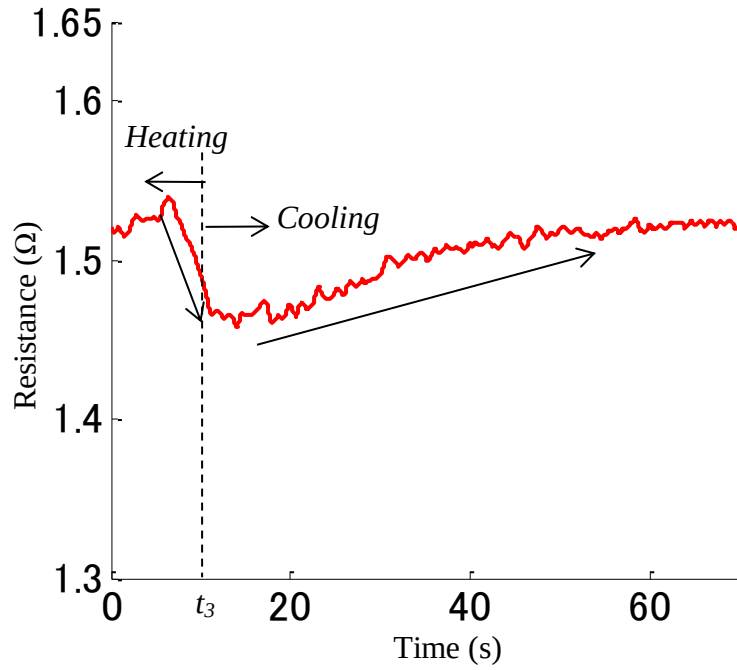


Fig. 4-11 Results of resistance with heating time 5s for SMA1
in ambient temperature 24°C

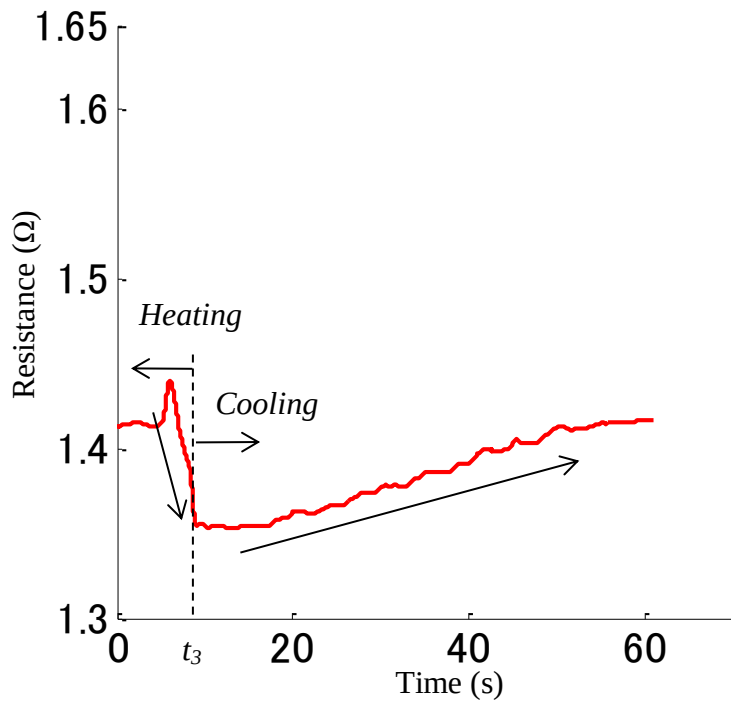


Fig. 4-12 Results of resistance with heating time 3s for SMA2
in ambient temperature 24°C

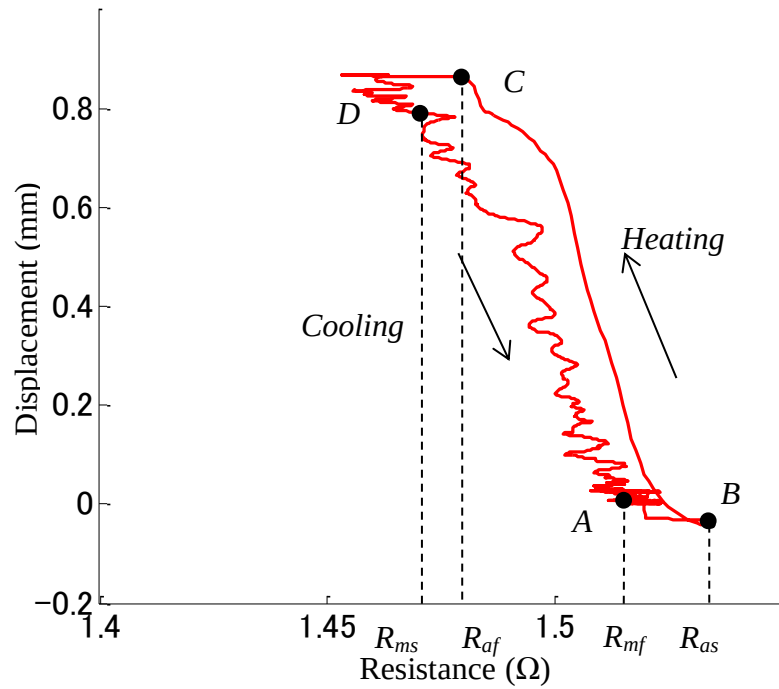


Fig. 4-13 Major hysteresis loop for SMA1 in ambient temperature 24°C

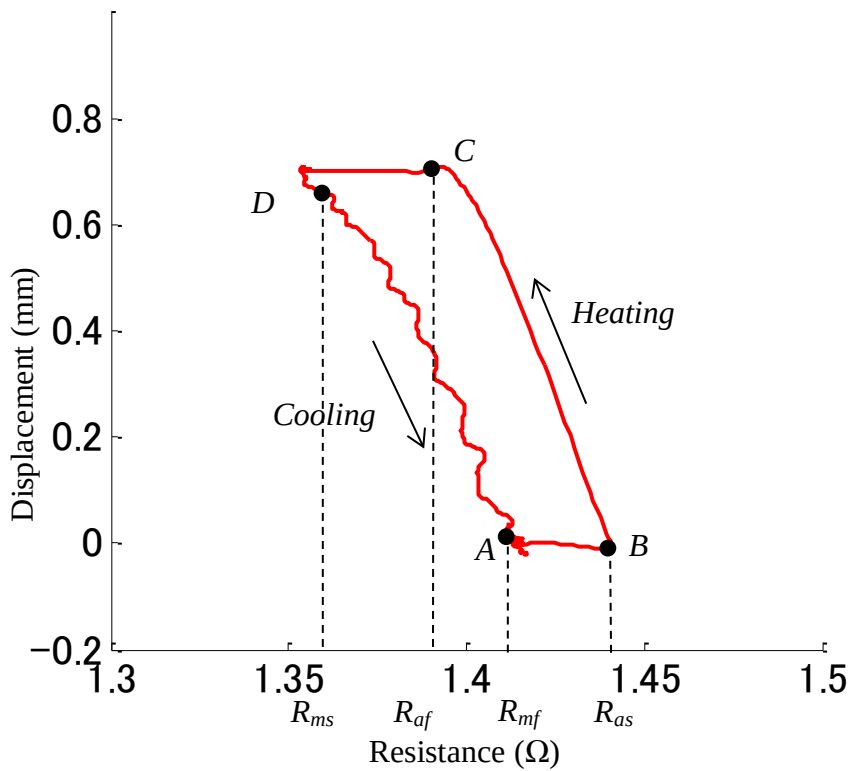


Fig. 4-14 Major hysteresis loop for SMA2 in ambient temperature 24°C

Fig. 4-13 and Fig. 4-14 show the phase resistance of major hysteresis loop of SMA1 and SMA2, respectively. In segment *AB*, the SMA wires extend quickly and complete the phase resistances transformation from R_{mf} to R_{as} ; in segment *BC*, the SMA wires shrink and the resistances decrease from R_{as} to R_{af} ; in segment *CD*, the resistances decrease from R_{af} to R_{ms} and the SMA wires cool but the output displacements remain practically unchanged; According to the criteria mentioned in chapter 3, the resistance decreases from R_{af} to R_{ms} with 10% declines in the output strain. In segment *DA* when the output displacements are less than 0.76mm and 0.64mm, the SMA wires start the transformation from austenite to martensite for SMA1 and SMA2 at *D*, respectively. More detailed information about the transformation resistances of SMA1 and SMA2 is shown in Table 4-2.

4.4.2 Tuning the PID Parameters

The PRFC is proposed here to improve on the slow response speed obtained with binary control. Fig. 4-6 shows the control arrangement of the PRFC where the resistance coordinator sends the phase resistance as input to SMA1 and SMA2. The PID controller should be tuned first to obtain proper parameters in the feedback control.

Fig. 4-15(i) shows the results of PID control using resistance as feedback to maintain the resistance of SMA1 at R_{ms} . When $K_p=500$, $K_i=0$, and $K_d=0$, the resistance increases quickly since the input voltage which is used to heat and maintain the SMA wire is not enough. As shown in Fig. 4-15(ii), this results in the output displacement decreasing quickly without any maintaining; when $K_p=4000$, $K_i=1$, and $K_d=0$, the output displacement is unstable because $K_i=1$ is too large and SMA is overheated, the resistance cannot be maintained at R_{ms} ; when $K_p=4000$, $K_i=0.5$, and $K_d=0$, the resistance can be maintained at R_{ms} from 38s to 50s and there is no steady-state error e . However, the output displacement (Fig. 4-15(ii)) is maintained at 0.83mm and there is long latency duration $T_m=12s$; when $K_p=4000$, $K_i=0.2$, and $K_d=0$, the resistance is maintained at R_{ms} and the output displacement is maintained around 0.76mm from 23s to 50s even if there is small steady-state error e . When the power is turned off from 50s, the output displacement declines quickly. Therefore, $K_p=4000$, $K_i=0.2$, and $K_d=0$, are selected as the parameters in the PID control. In addition, the PI control can meet the need in the experiment. Therefore, parameter K_d is set to be zero in the PID controller.

According to the same method, the parameters for SMA2 are tuned. Fig. 4-16(i) and Fig. 4-16(ii) show the results of PID control using resistance as feedback and output displacement, respectively. It clearly shows that $K_p=4000$, $K_i=0.18$, and $K_d=0$, are the suitable parameters to maintain the output displacement at 0.64mm.

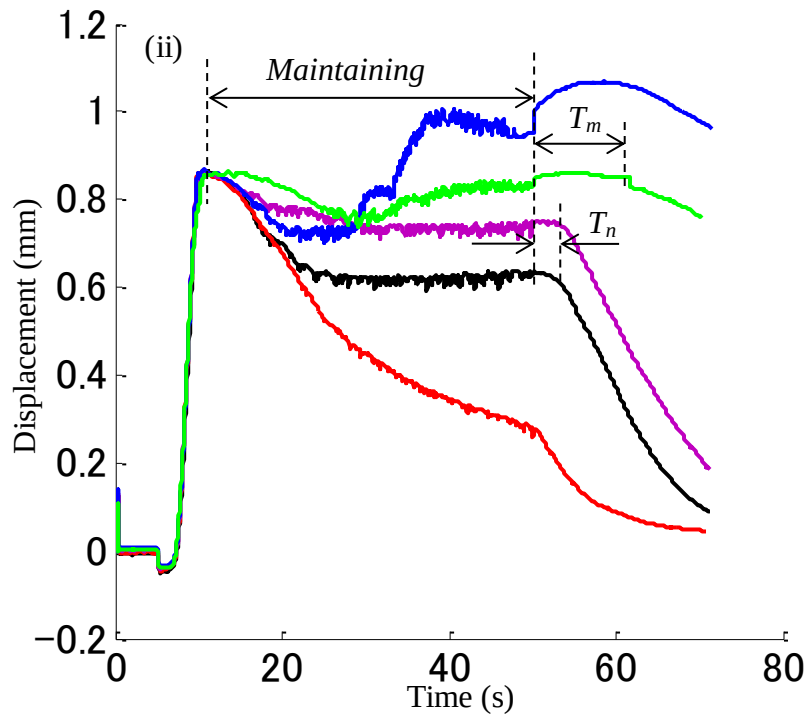
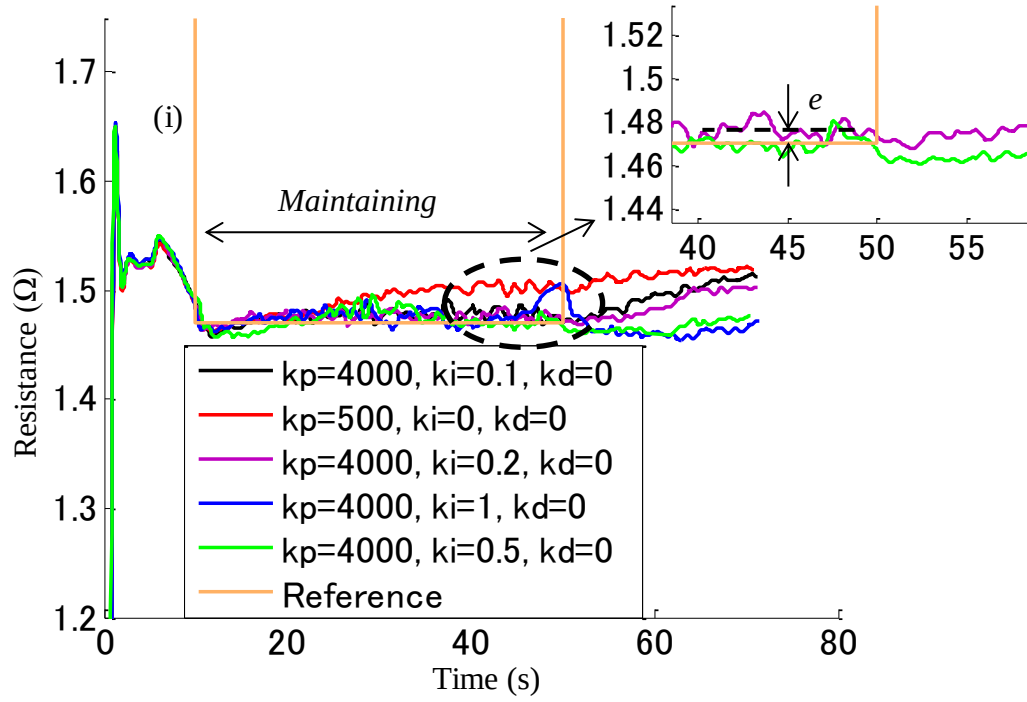


Fig. 4-15 Results with different PID parameters for SMA1

in ambient temperature 24°C

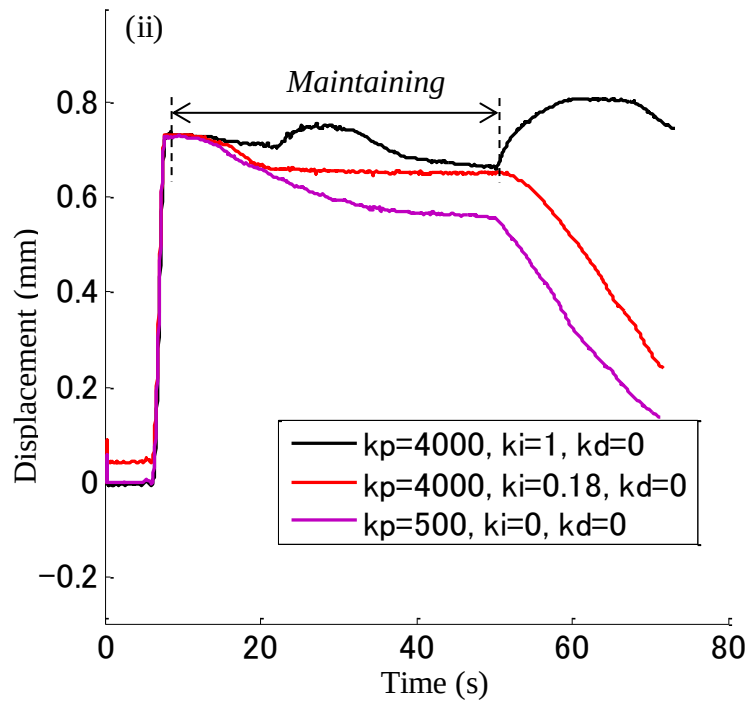
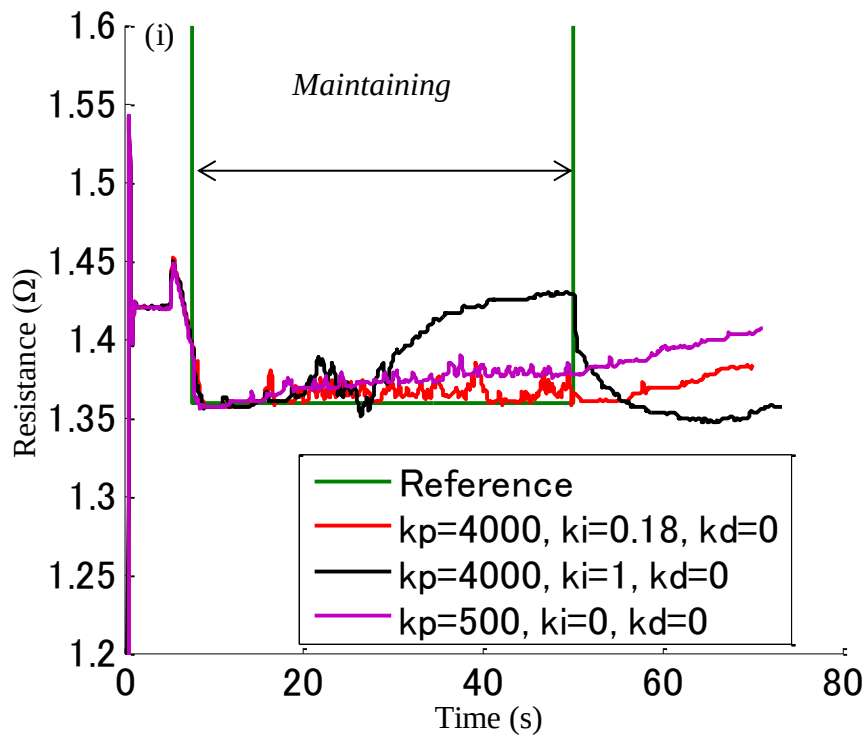


Fig. 4-16 Results with different PID parameters for SMA2
in ambient temperature 24°C

4.4.3 Results with PRFC

The two SMA wires will be actuated separately, using these parameters to test the possibility of obtaining the results discussed in Fig. 4-4. Fig. 4-17 shows the results with PRFC for SMA1 when the power for SMA2 is turned off. Fig. 4-17(i) shows, in the heating process, the input voltage is V_h which can make a maximum output displacement without overheating. In the maintaining process, the resistance is maintained at R_{ms} using resistance as feedback. Fig. 4-17(iii) shows the results of output displacement. It clearly shows the heating, maintaining, and cooling processes and the output displacement is maintained successfully during the maintaining section. Fig. 4-18 shows the results with PRFC for SMA2 when the power for SMA2 is turned off. Fig. 4-18(i) shows that the input voltage is 5V and the heating time is 3s to obtain a maximum output displacement during the heating process. Fig. 4-18(iii) shows the results of output displacement of SMA2. During the maintaining section, the output displacement is maintained at 0.64mm from 123s to 185s successfully.

With the results of SMA wires actuated separately, the two SMA wires will be actuated together to demonstrate the results of rapid response speed with PRFC. Fig. 4-17(ii) and Fig. 4-18(ii) are plots of the variations of the actual resistances of SMA1 and SMA 2 using the phase resistances as the feedback. And the resistance is maintained at R_{ms} successfully. When the resistance of SMA2 reaches R_{af} at $C=123s$, SMA1 cools quickly from the phase resistance R_{ms} ; then when the resistance of SMA1 reaches R_{af} at $E=185s$, SMA2 cools quickly from the phase resistance R_{ms} ; during CE , there is no output displacement though the resistances of SMA2 increase from R_{af} to R_{ms} . The latency duration of the cooling process is shortened, combining the heating process AC of SMA2 and the cooling process CD of SMA1.

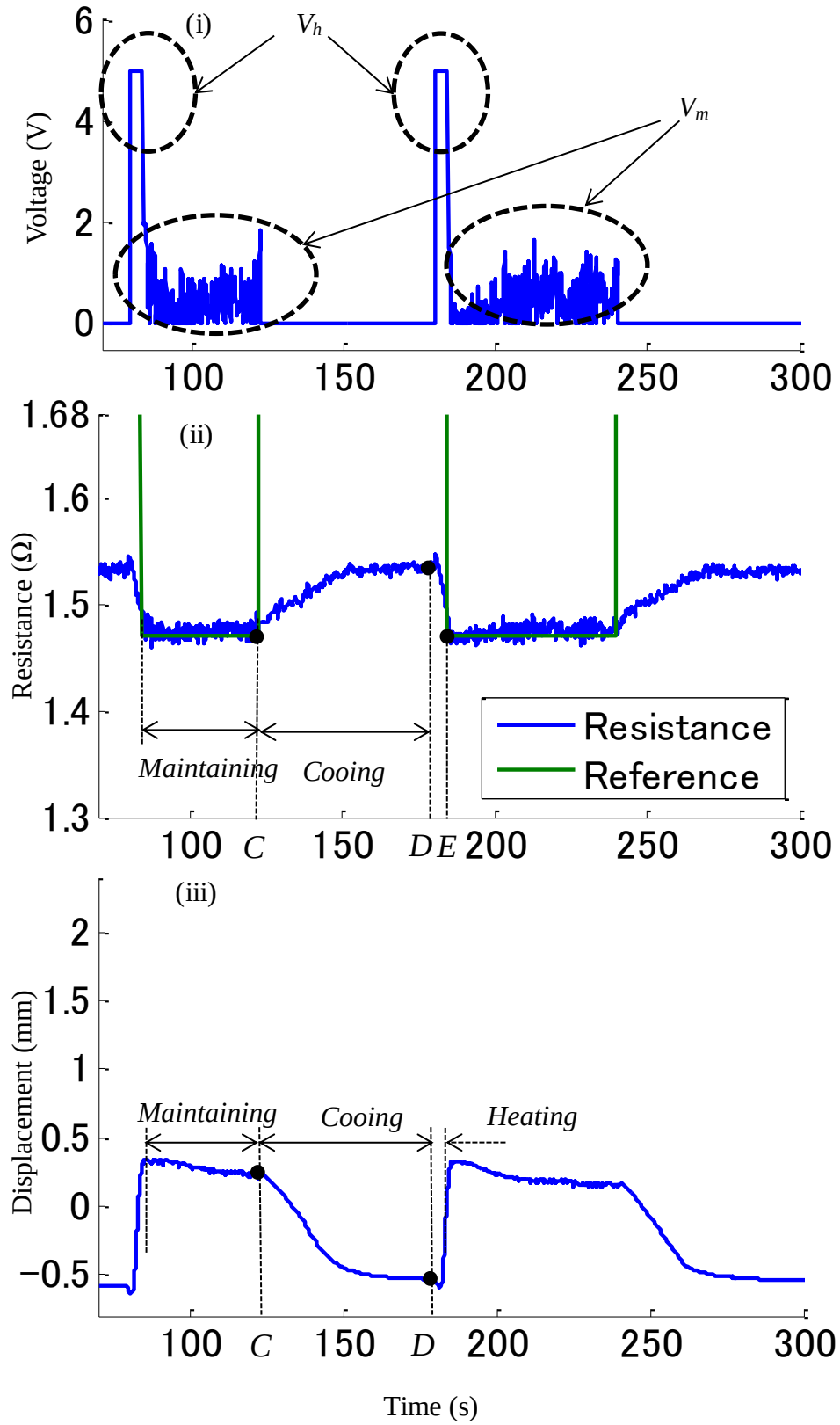


Fig. 4-17 Results with PRFC for SMA1 in ambient temperature 24°C

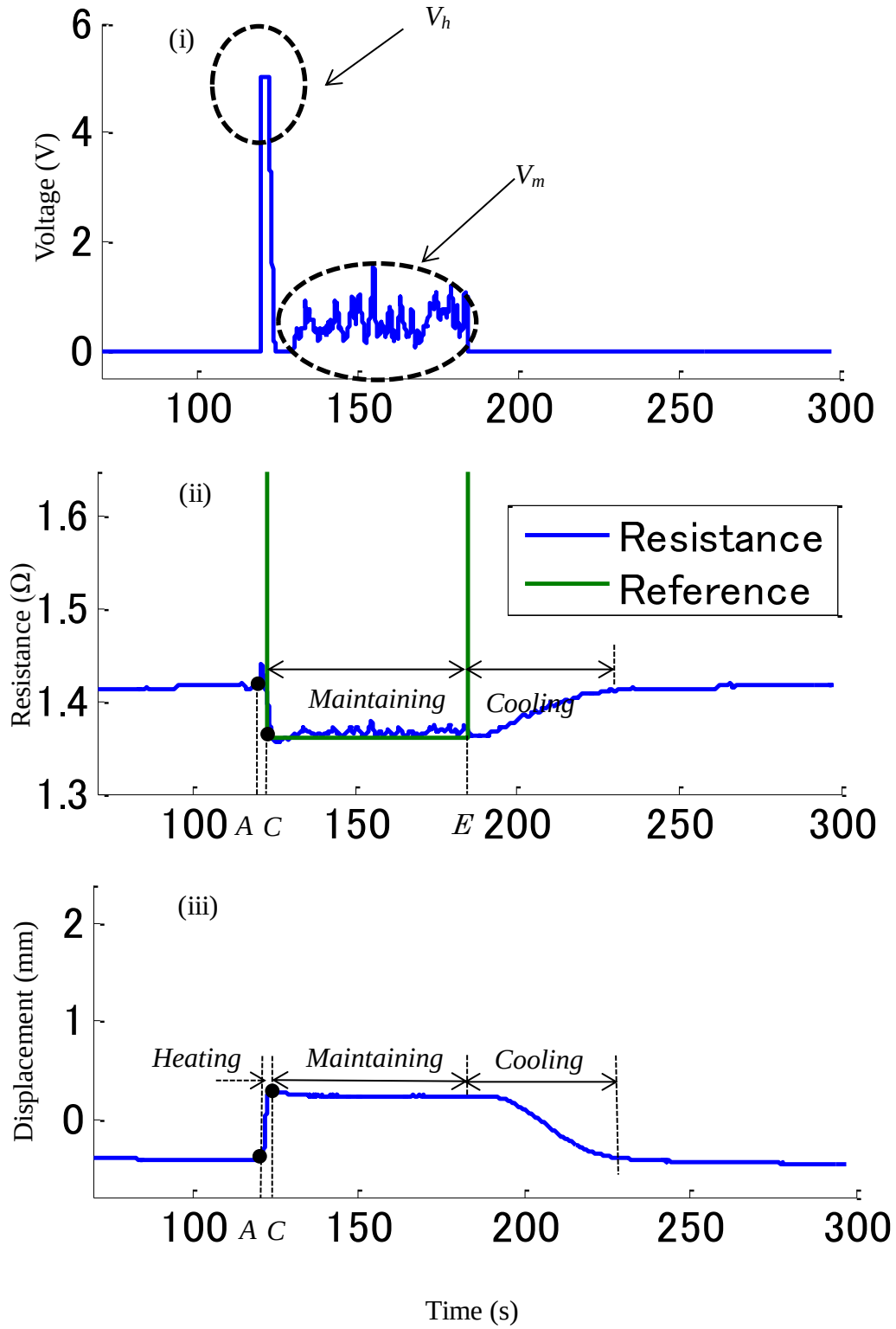


Fig. 4-18 Results with PRFC for SMA2 in ambient temperature 24°C

The output displacement is illustrated in Fig. 4-19. It shows that the maximum output displacement (1.47mm) is the sum of both SMA wires. Part 1 and part 2 are the available results of cycle for SMA2 and SMA1, respectively. The detailed output displacement is shown in Fig. 4-20 with two cycles.

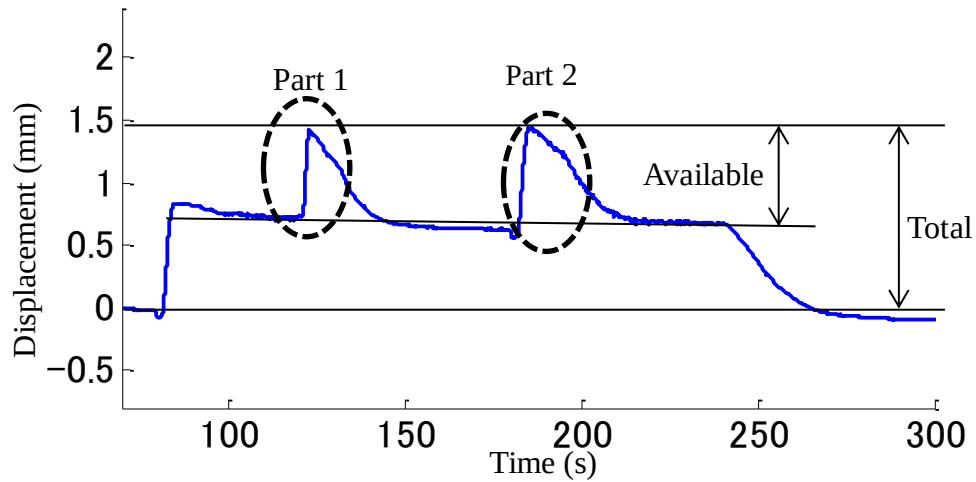


Fig. 4-19 Total output displacement with PRFC in ambient temperature 24°C

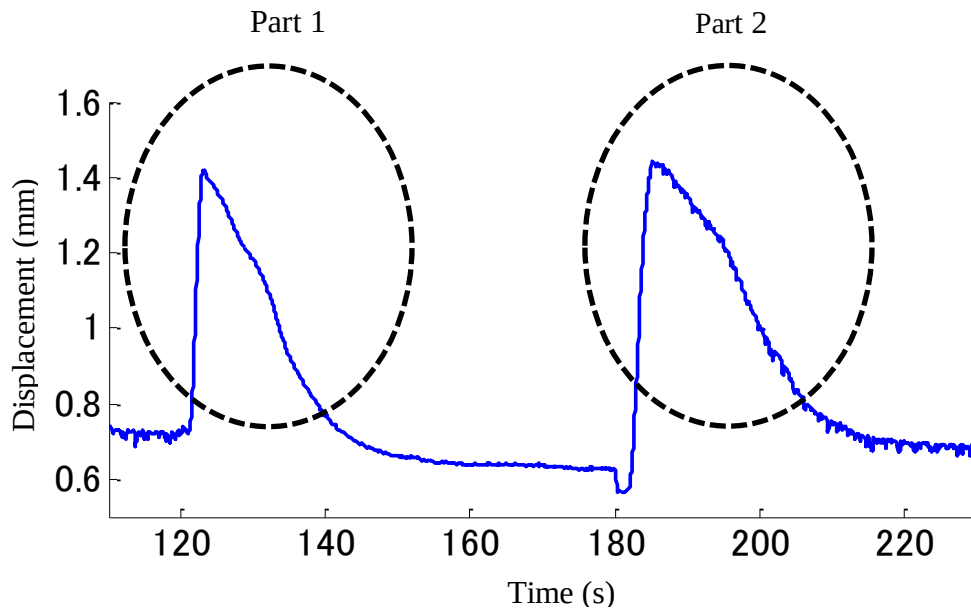


Fig. 4-20 Detailed output displacement with two cycles for PRFC
in ambient temperature 24°C

4.5 Consideration and Discussion

The arrangement proposed here improves the response speed of the thick SMA wires significantly in comparison with the binary control. There are , however, a few critical points needs further consideration.

1. Since the maximum output displacement of both SMA wires is different. To obtain clear and accurate results, part 1 will be selected to compare with binary control of SMA2, and part 2 will be compared with binary control of SMA1. As illustrated in Fig. 4-21, the output displacement with PRFC starts to extend at 10s during the cooling process. According to the criteria in chapter 3, when the output displacement is less than 90% of the maximum displacement, the SMA1 starts the transformation from martensite start phase to martensite finish phase at 13s, and the latency duration with PRFC $T_{Lp}=3s$. The SMA1 completes the phase transformation at $e=46.5s$. Fig. 4-22 shows the results with PRFC for SMA2. The SMA2 completes the phase transformation at $e=43s$. More detailed information is listed in Table 4-3. The average cycle time for the binary control and proposed method is 54.5s and 39.8s, respectively. The response improvement is given by

$$\partial = \frac{54.5 - 39.8}{54.5} = \frac{14.7}{54.5} = 27.1\% \quad (4-8)$$

Table 4-3 Parameters of the SMA1 and SMA2

	Binary control		PRFC	
	T_{cd}	Cycle time	T_{Lp}	Cycle time
SMA1	13s	54s	3s	41.5s
SMA2	14s	55s	2s	38s

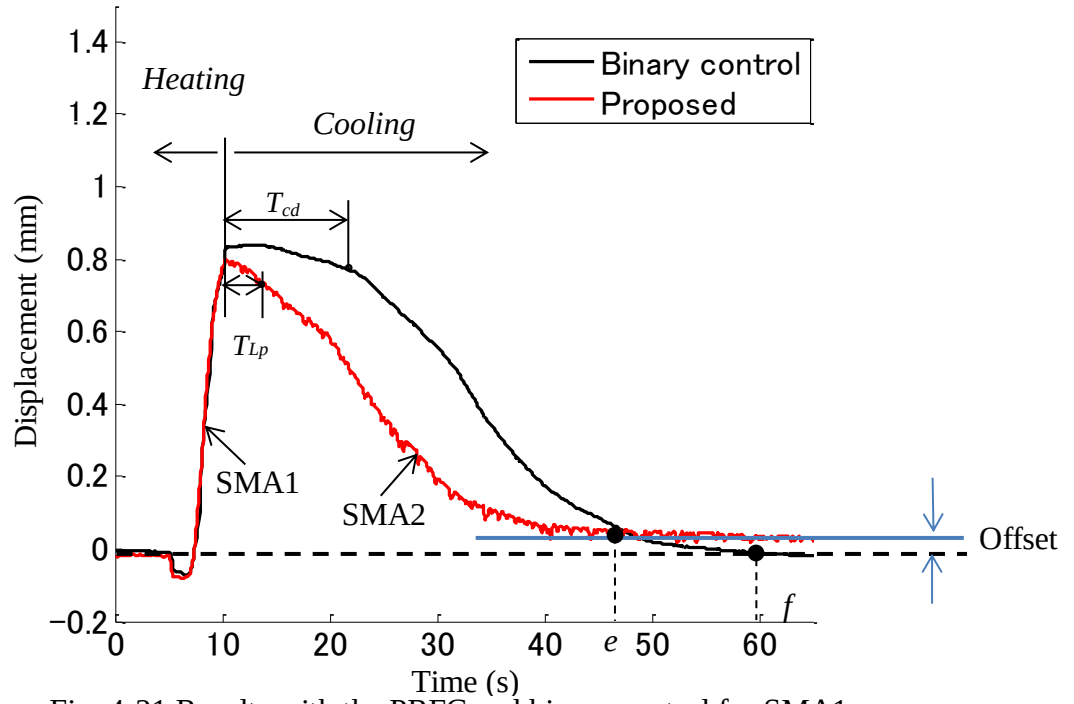


Fig. 4-21 Results with the PRFC and binary control for SMA1
in ambient temperature 24°C

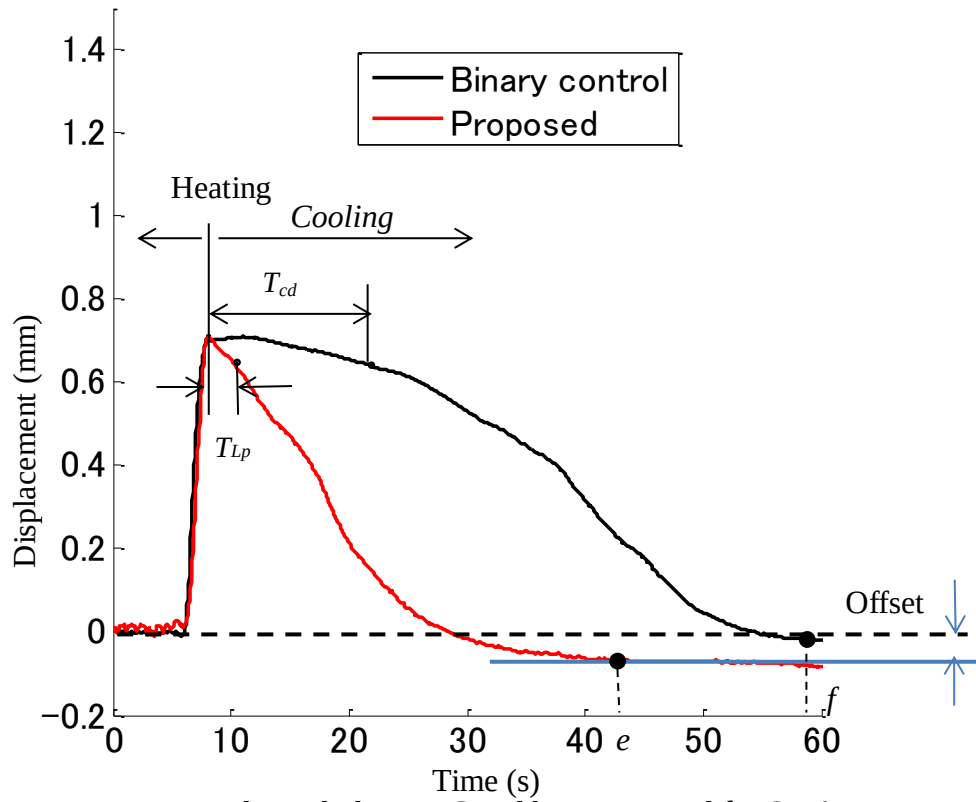


Fig. 4-22 Results with the PRFC and binary control for SMA2
in ambient temperature 24°C

2. Theoretically, the MOSFET should be turned off during the cooling process in order to obtain rapid cooling response speed. One limitation is that the microcontroller needs time to read the analog inputs voltage V_1 , V_2 and V_3 to calculate the resistance by turning on the MOSFET and turning off it when the reading is finished, which makes longer time for the SMA finishes phase transformation from austenite to martensite. Fig. 4-23 shows the results with or without reading the input voltage to calculate the resistance with ambient temperature 24°C. There will be small current through the SMA wire by turning on MOSFET when reading the analog input voltage, resulting in SMA finishes the martensite phase at $f_2=71s$ instead of $f_1=68s$. It means that the cooling speed will be slower by calculation the resistance of SMA during cooling process even if the heating speed is the same. Therefore, when the output displacement with binary control is detected by displacement sensor, the resistance is calculated as well by reading the analog inputs in order to compare the output displacement with proposed method. In addition, as shown in Table 4-2, there is small difference for the resistance of SMA wires because the calculation of resistance is affected by the microcontroller, specimen, driver circuit and power source.
3. As shown in Fig. 4-21 and Fig. 4-22, the offset of two cycles during cooling process is 0.05mm and -0.08mm for SMA1 and SMA2 respectively. The output displacement (Fig. 4-21) is from SMA1 and SMA2 during the heating and cooling processes for the proposed method, respectively. Since the maximum output displacement of SMA2 is 0.71mm, the output displacement with PRFC for SMA1 declines from 0.81mm and can not reach to zero position during the cooling process. Then, the offset is positive; since the maximum output

displacement of SMA1 is 0.81 mm, the output displacement with PRFC for SMA2 (Fig. 4-22) declines from 0.71mm and the offset is negative. In addition, the insulation joint which is used to prevent short circuiting needs to be tight enough to connect SMA wires to prevent offset caused by loosening.

4. As shown in Fig. 4-24, the results of output displacement are very similar with heating time 5s for 5 tests, however, the offset for maximum output displacement and martensite finish displacement are 0.02mm and 0.03mm, respectively. It means there will be small offset for output displacement in each test with the same heating and cooling time because the output displacement is affected by hysteresis effect and sensitive to ambient environment. Therefore, the offset for the output displacement is unavoidable.

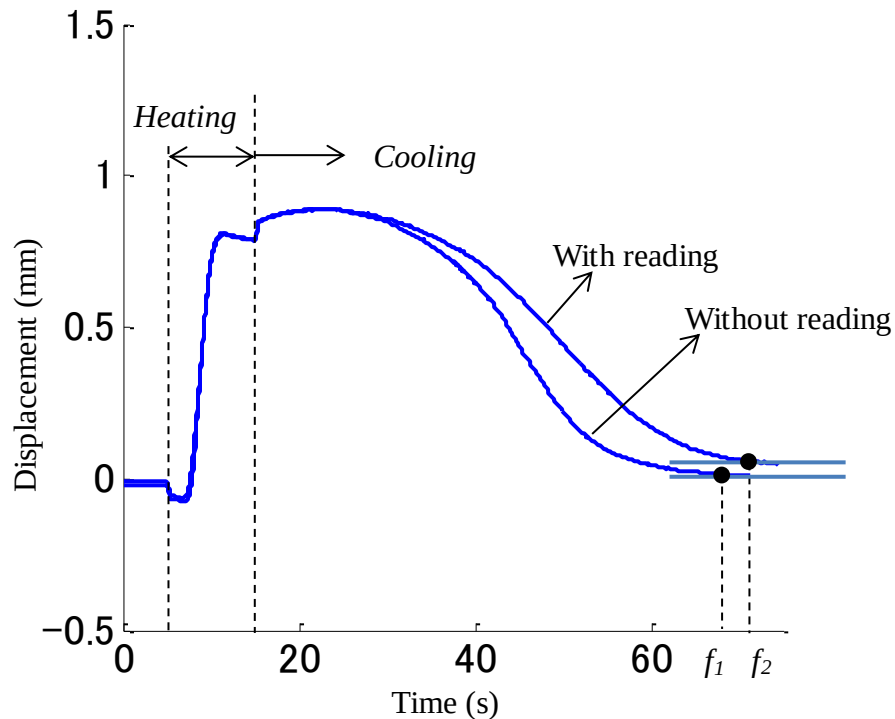


Fig. 4-23 Binary control with or without resistance calculation
in ambient temperature 24°C

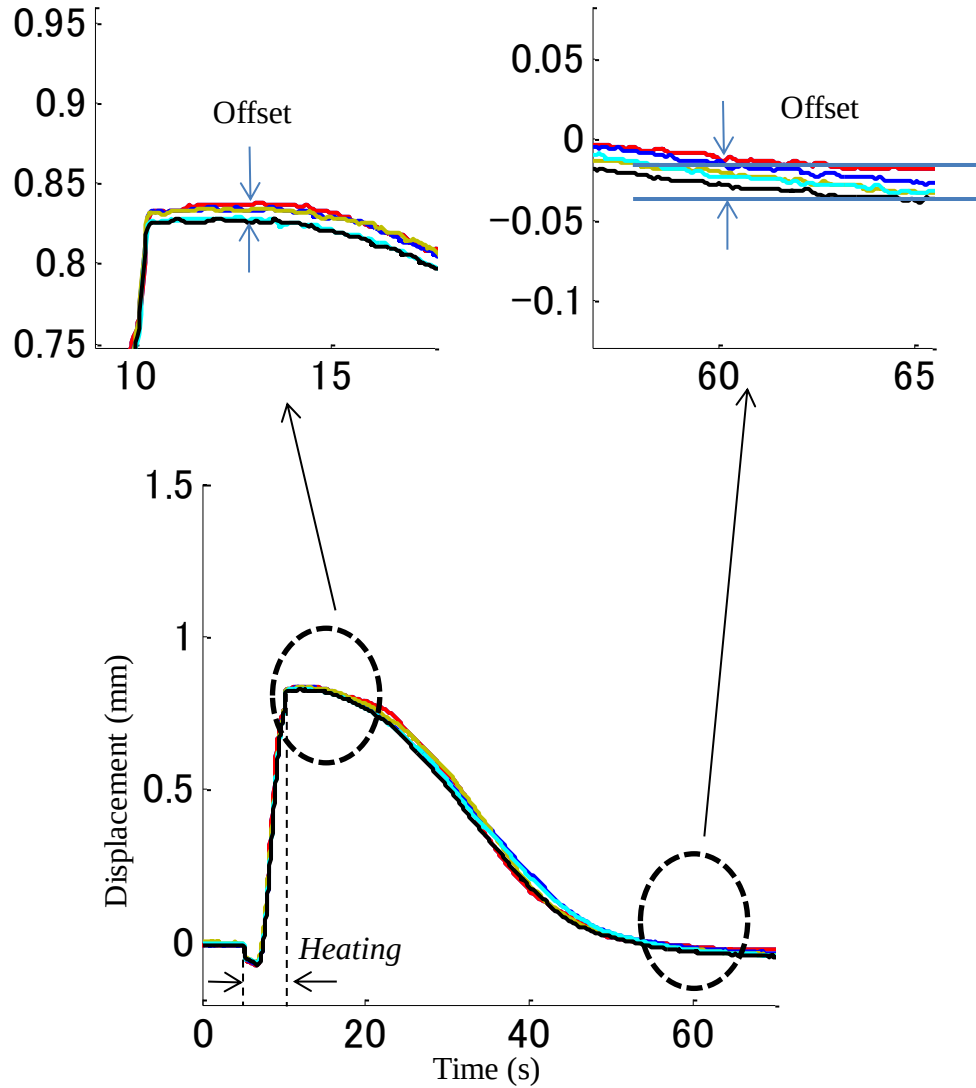


Fig. 4-24 Results with the binary control for 5 tests
in ambient temperature 24°C

5. For the two cycles shown in Fig. 4-20, the maximum output displacement is based on one single SMA wire even though two SMA wires are used in the experiment with PRFC. The total output displacement is 1.47mm, however the effective output displacement is 0.71mm and 0.81mm. Therefore, the results of rapid response speed is achieved on the cost of maximum output displacement

which is a limitation for the proposed method.

6. The results only show the improvement of cooling speed with shortening the latency duration T_{cd} , the latency duration T_{ab} still exists even though is small compared with T_{cd} . As shown in Fig. 4-15, there is still small hysteresis duration T_n when the output displacement is maintained at martensite start displacement during the cooling process when the power is turned off. Moreover, there is short latency duration T_{Lp} with the PRFC. It means the latency duration caused by hysteresis effect cannot be eliminated totally. But it does not deny the effectiveness of the proposed method.
7. Comparing with the research in reference [5], there is no limitation caused by Peltier device. The advantages are as follows.
 - (i) There is no need to heat the Peltier in order to heat SMA, resulting in saving energy.
 - (ii) Since the two SMA wires are connected by insulation joint, there is no heat transfer between adjacent segments.
 - (iii) The SMA wires will not shift to adjacent units, as the SMA wire shrinks and expands. Therefore, there is no error caused by adjacent segment.
 - (iv) At last, the experimental apparatus is light and convenient because of without Peltier models in the apparatus.

4.6 Chapter Summary

An SMA actuator structure using two connected SMA wires which is able to generate rapid response for thick SMA actuators is proposed. The results with the proposed PRFC (Phase resistance feedback control) using the concept of phase transformation

resistances that divided the hysteresis loop into four parts, enable a shortening of latency duration with two connected SMA wires coordinated to use the phase resistances as feedback than with the binary control. Experimental results also demonstrated that the average cycle time was 27.1 percent shorter than with binary control.

To accurately identify phase resistances, experiments have shown that it is important to determine the major hysteresis loop. It is also important to avoid overheating the SMA wires by controlling the heating time which could otherwise slow the response speed greatly.

CHAPTER 5:

IMPROVEMENT OF RESPONSE SPEED USING PHASE RESISTANCE AND DISPLACEMENT AS FEEDBACK

5.1 Introduction

There are many researches on improvement of the response speed in the past as mentioned in chapter 3 and chapter 4 [74, 80]. Conventional SMA actuator systems consist of heating the entire length of SMA wire with electric current and cooling with natural convection [62, 67], the wire shrinks or extends at the same time. There are long latency durations for thick SMA wires, the response speed is slow which has been discussed in chapter 4. In contrast, an approach, which separately controls two connected SMA wires, making individual SMA wire can shrink or extend at different time with the same maximum output displacement as an entire SMA wire, is proposed in this chapter. The motivations will first be explained. In section 5.3 and 5.4, the method and results will be described. Some discussions and conclusions about the results are also presented in section 5.5 and 5.6, respectively.

5.2 Motivation and Target

In chapter 4, the PRFC demonstrates more rapid response speed than binary control. However, the maximum output displacement is only detected from one single SMA wire.

Here, an alternative control method, phase resistance and displacement feedback control (PRDFC), combining both the phase resistance and displacement as feedback, is proposed to obtain rapid response speed as well. It minimizes cooling time by shortening the long latency duration of thick SMA wires and the total output displacement is the same as traditional control method. Experimental results here show that rapid response speed is achieved using this method in comparison with the case in which only displacement is used as feedback.

5.3 Method

5.3.1 Phase Resistance with Displacement Feedback Control (PRDFC)

Traditionally, a data collected from a displacement sensor can be used as feedback for only one SMA wire in a position control. It is difficult to control the output displacements of two SMA wires at the same time when they shrink or extend randomly because they will interfere with each other. To prevent the two SMA wires from mutual interference and obtain accurate position control results, a few technical issues must be considered:

1. When the SMA wire completes the transformation from martensite to austenite, it needs to be maintained in martensite starting phase which is ready to extend without any changes in the output displacement;
2. When one SMA wire completes the transformation from martensite to austenite, the other needs to start the phase transformation quickly to guarantee continuity of output displacement, or vice-versa.

The critical aspect of the PRDFC method is to shorten the total cooling time by

switching the reference input from phase resistances to displacement with two connected SMA wires that are coordinated, or vice-versa.

To justify the concept of PRDFC, a step signal is used as reference input for a position control of SMA actuator first. Fig. 5-1 shows the basic theory behind this method, using the definitions in Fig. 4-2, Fig. 4-3 and Table 4-1, and it can be explained as follows.

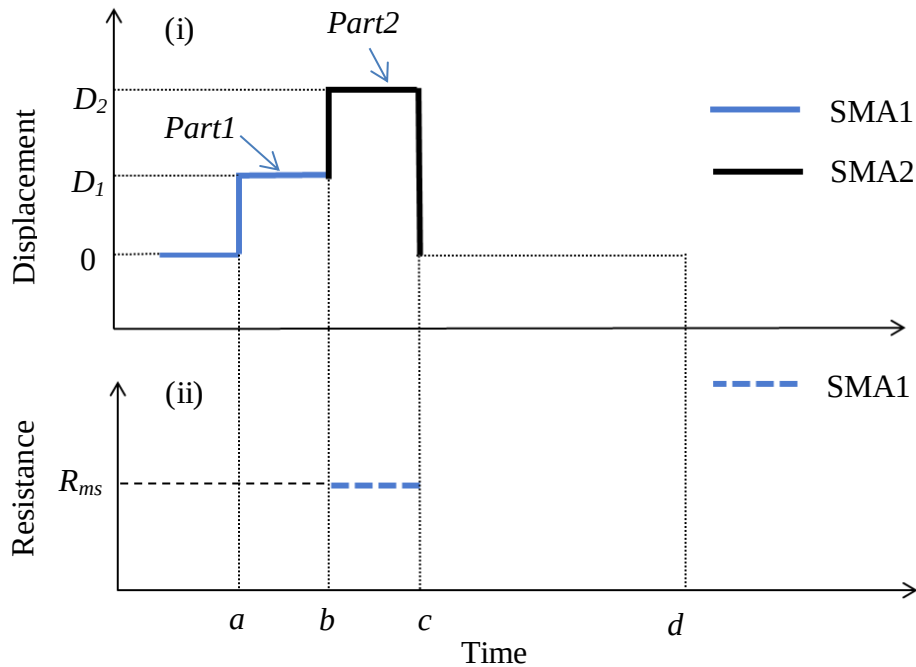


Fig. 5-1 Schematic of step reference for the PRDFC method

As shown in Fig. 5-1(i), the step signal is divided into two parts, part 1 is used as reference input signal for SMA1, part 2 is used as reference input signal for SMA2. Since the data collected from the displacement sensor can be used as feedback for only one SMA wire, the SMA wire need to be maintained at R_{ms} to prevent from any changes in the output displacement when the other one extends or contracts. As shown in Fig. 5-1(ii), the reference input switches from displacement to resistance for SMA1 at b , and

during section bc the output displacement is maintained. This means that only one SMA wire provides the output displacement in each part.

During section ab , part 1 is used as the reference displacement for SMA1, and once the total output displacement reaches D_1 at b , the reference input quickly switches from displacement to resistance and the resistance of SMA1 is maintained at R_{ms} . The result is that there is no displacement output from SMA1 during section bc .

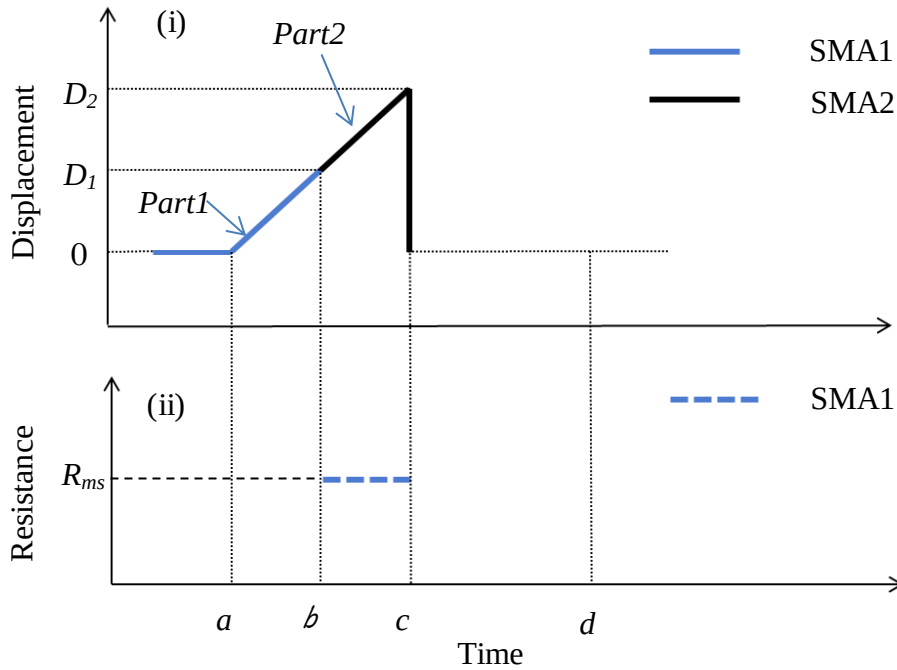


Fig. 5-2 Schematic of ramp reference for the PRDFC method

During section bc , part 2 is used as reference displacement input for SMA2 from b , immediately. The data collected from the displacement sensor can be used as feedback to control the position of SMA2 because SMA1 is maintained in martensite starting phase and it is ready to extend without any changes in the output displacement.

During section cd , once the total output displacement reaches D_2 at c , both the power for SMA1 and SMA2 are turned off to achieve quickly cooling speed. Since SMA1 has

completed the phase transformation from austenite to martensite starting during section bc , the latency time T_{cd} of SMA1 is shortened, making it possible to obtain fast cooling response speed during section cd . In order to obtain the maximum output displacement of SMA continuously, the reference input needs to increase step by step. Since the sampling time is 0.05s, the time of each step for reference input needs to be less than sampling time. In this chapter, the ramp signal is used in the position control to get the maximum output displacement. Fig. 5-2 shows the basic theory behind this method as well, using ramp signal as reference input. Part 1 is used to obtain the maximum output displacement of SMA1. Then, the R_{ms} of SMA1 can be used as feedback to maintain the output displacement of SMA1.

5.3.2 Control System

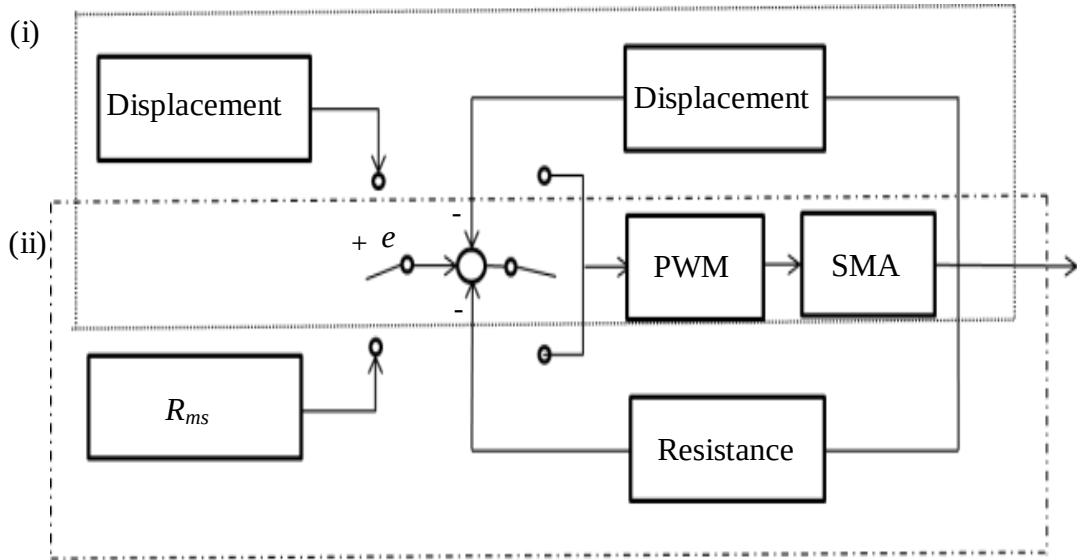


Fig. 5-3 Block diagram of PRDFC, (i) Displacement feedback control; (ii) Phase resistance feedback control

As discussed in the introduction section, many efforts have been made to model and control behavior of SMA actuators. In this section, a new control system combined by

displacement and resistance feedback is proposed here to apply the PRDFC method to control SMA actuator. Fig. 5-3(i) and Fig. 5-3 (ii) show the displacement and resistance feedback system, respectively. The control system switches from resistance to displacement feedback control for the position control of SMA1 or SMA2; the control system switches from displacement to resistance feedback control to maintain the output displacement of SMA1 or SMA2. The reason that switches control system between displacement feedback control and resistance feedback control is that there is no displacement output from SMA wires by maintaining the resistance of SMA wires at R_{ms} when they complete phase transformation from martensite to austenite, making it possible to obtain fast response speeds during the cooling processes by shortening the latency duration without reducing the accuracy of position control.

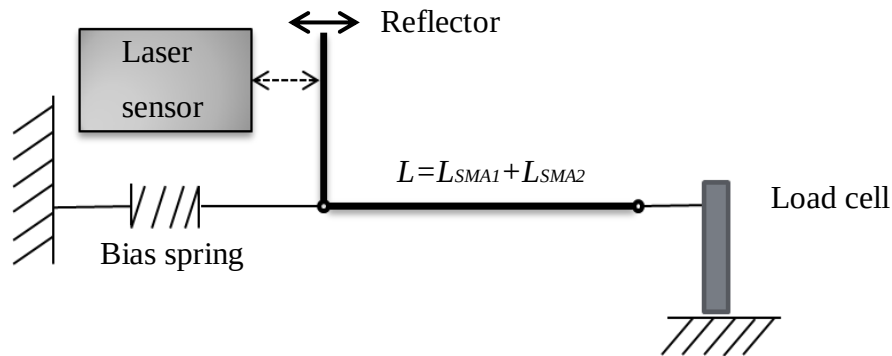


Fig. 5-4 Schematic of the experimental setup for displacement feedback control

For the displacement control of SMA1 or SMA2, the displacement is measured by the displacement sensor and resistance is calculated by Eq. (3-1), using the data sent by microcontroller. To be able to use the phase resistance and displacement as feedback, a PI controller is installed. The PI controller is denoted by PWM which is sent to MOSFET and converted to heat voltage. It can be calculated by Eq. (4-6) and Eq. (4-7).

The experimental setup is the same as Fig. 4-7 with PRDFC. To be able to compare PRDFC with traditional displacement feedback control, it is necessary to use the same length of SMA wire by sending the same PWM value (calculated by PID controller in Fig. 4-8) to heat the SMA wires. Then, as shown in Fig. 5-4, the length of SMA wire with traditional displacement feedback control, L , is expressed by

$$L=L_{SMA1}+L_{SMA2} \quad (5-1)$$

where L_{SMA1} and L_{SMA2} are the length of SMA1 and SMA2, respectively.

5.4 Results

5.4.1 Tuning PID Parameters

In order to obtain good results with PRDFC, the parameters of resistance feedback in the PID controller based on Eq. (4-6) are the same as used in chapter 4. For the parameters of displacement feedback, it needs to be tuned again. Fig. 5-5 shows the results of PI control using displacement as feedback. When $K_p=500$ and $K_i=0$, the maximum output displacement is small and there are large steady-state error since the input voltage which is used to heat the SMA wire is small. When $K_p=1000$ and $K_i=0$, the maximum output displacement increases. However, there is still steady-state error. When $K_p=1000$ and $K_i=0.2$, the tracking performance is the best. With $K_p=1000$ and $K_i=1$, the output displacement is the worst since the input voltage changes largely shown in Fig. 5-6.

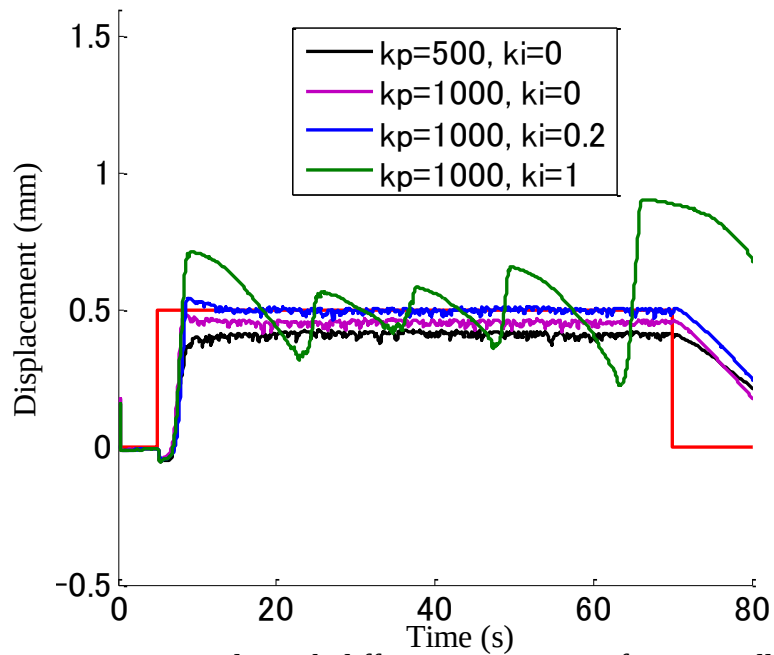


Fig. 5-5 Results with different parameters of PI controller
in ambient temperature 24°C

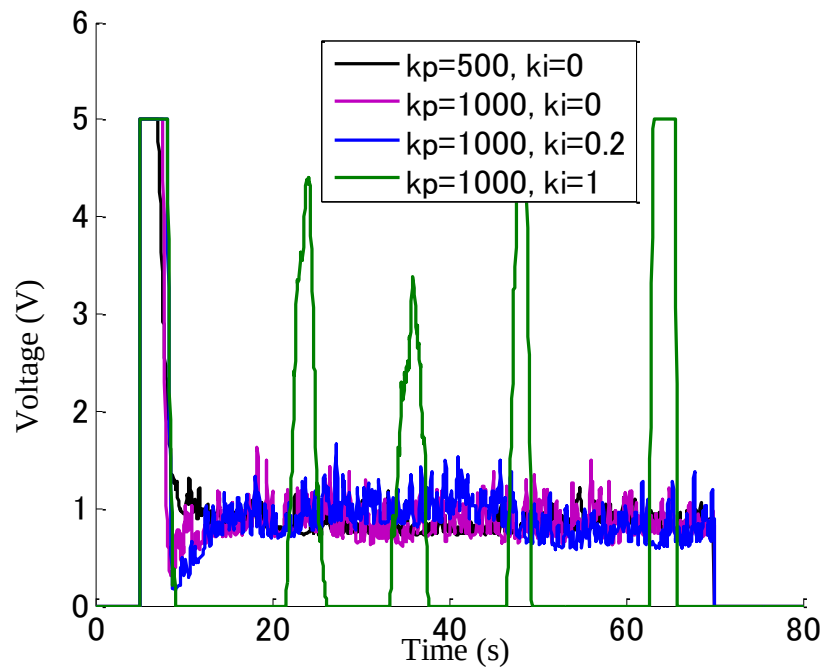


Fig. 5-6 Input voltage for different parameters of PI controller
in ambient temperature 24°C

According to the method shown in Fig. 5-1, experiments are conducted with step signal as reference input. The maximum output displacement of step is 1.4mm, and then the maximum output displacements for SMA1 wire are 0.8mm (0.01mm offset from the maximum output displacement 0.81mm) which leads to a major hysteresis loop of displacement-to-resistance, making it possible to use the phase resistances as feedback during the phase resistance feedback control. As shown in Fig. 5-7, the resistance of SMA1 decreases from 10s since the displacement is used as feedback from 10s to 50s. From 50s to 90s, the resistance of SMA1 is maintained at R_{ms} . As shown in Fig. 5-8, the output displacement is unchangeable and maintained at 0.74 mm during the maintaining period and the SMA1 completes the cooling process at $t=135s$. Therefore, it is possible to actuate SMA2 using the displacement as feedback from 50s to 90s because the SMA2 will not be interfered by the output displacement of SMA1.

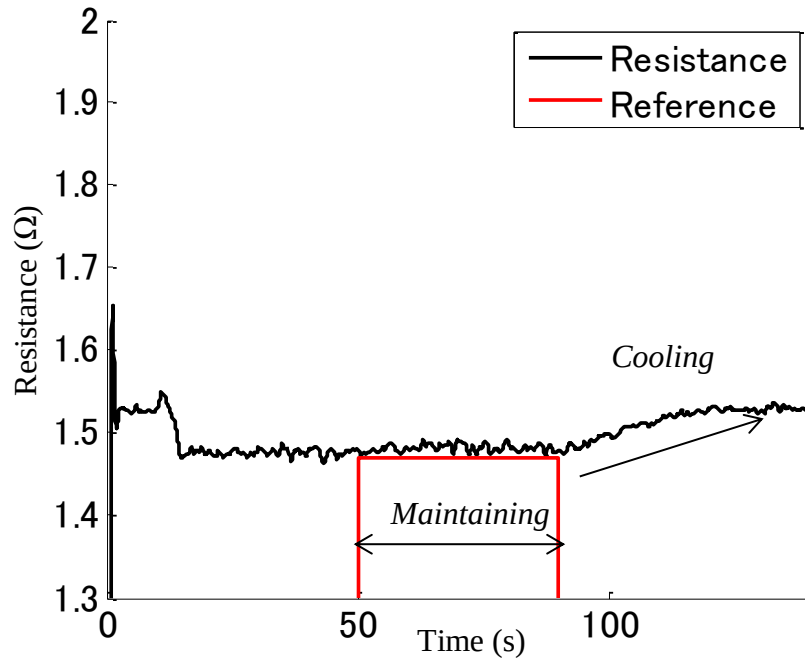


Fig. 5-7 Results of resistance for SMA1 with PRDFC in ambient temperature 24°C;

resistance control: $K_p=4000$, $K_i=0.2$

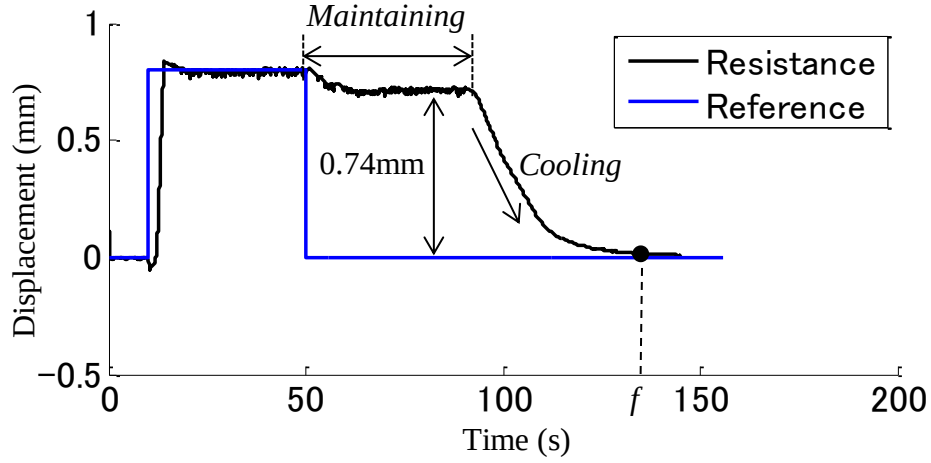


Fig. 5-8 Results of output displacement for SMA1 with PRDFC

in ambient temperature 24°C

5.4.2 Results with PRDFC

The experimental results of the proposed PRDFC and conventional displacement feedback control (based on Eq. (4-6) with $K_p=1000$ and $K_i=0.2$ as parameters, $e(t)$ is the signal error of displacement) are shown in Fig. 5-9. And the traditional method leads to latency more latency duration ($T_{cd}=5.5s$) than proposed method, which is caused by hysteresis effect of SMA (same phenomenon observed in Fig. 3-9). It is observed that the proposed PRDFC behaves more rapid response speed than the traditional displacement feedback control during the cooling process from 90s to 150s, though both systems in this test have similar tracking trajectory during the heating process from 10s to 90s. Since during tracking period of SMA2 from 50s to 90s, the latency duration of SMA1 is shortened, which leads to rapid cooling speed during the cooling process from 90s when the power is turned off. According to criteria to decide the martensite finish time with horizontal line mentioned in section 3.5, the proposed and traditional method complete the cooling process at $e=138s$ and $f=148s$, respectively.

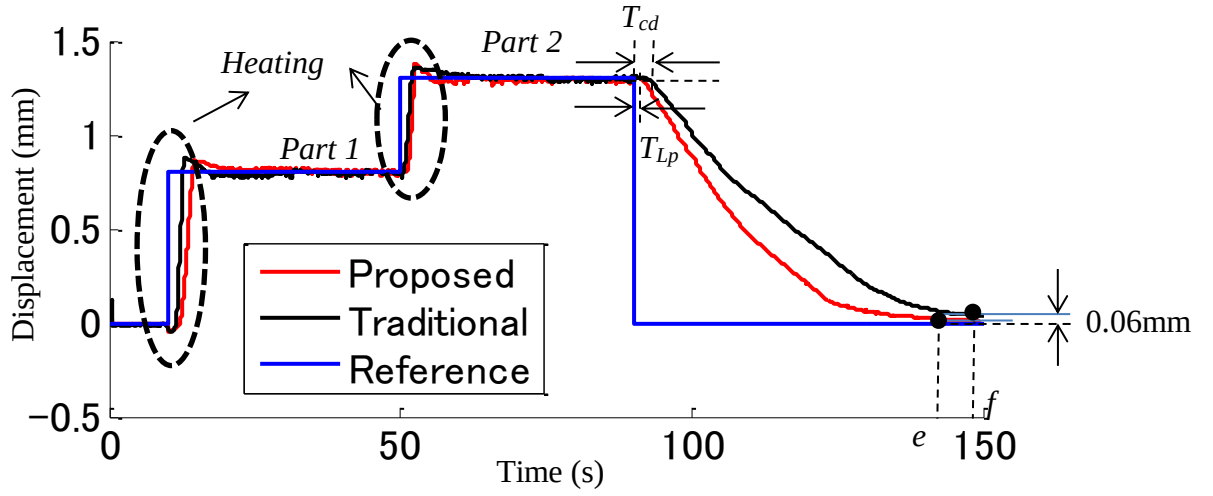


Fig. 5-9 Results of PRDFC and traditional method in ambient temperature 24°C;
displacement control: $K_p=1000$ and $K_i=0.2$; resistance control: $K_p=4000$ and $K_i=0.2$

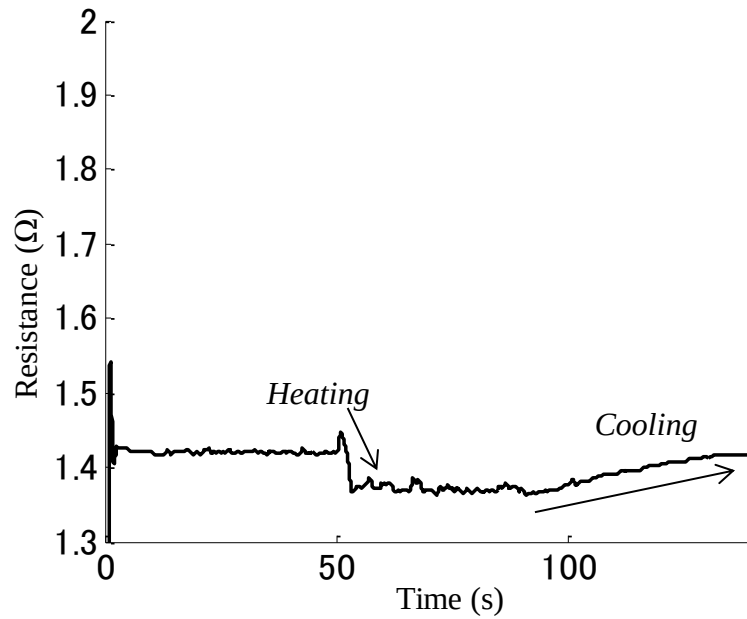


Fig. 5-10 Results of resistance for SMA2 with PRDFC in ambient temperature 24°C;
displacement control: $K_p=1000$ and $K_i=0.2$

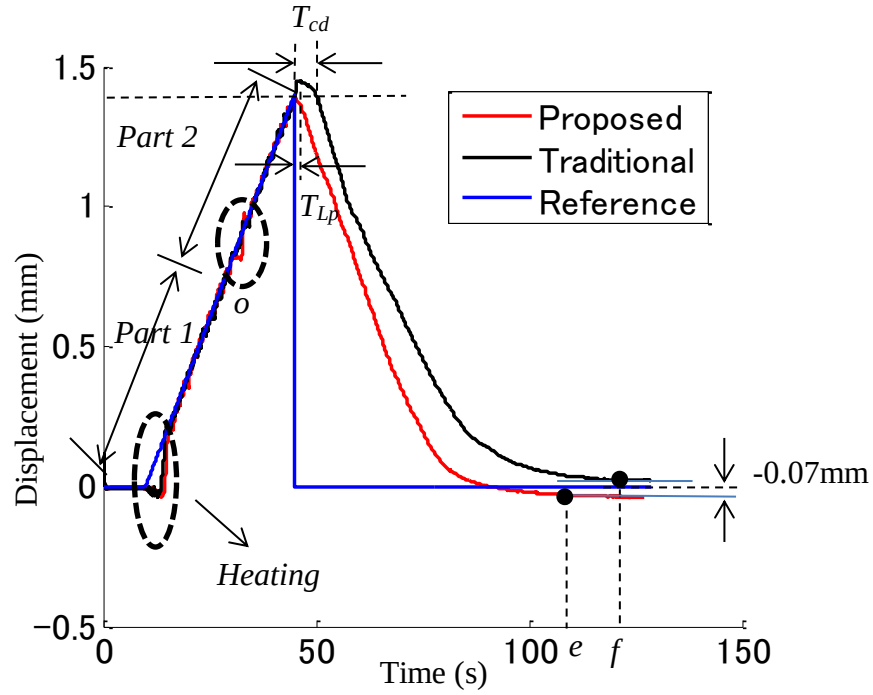


Fig. 5-11 Results of PRDFC and traditional method in ambient temperature 24°C;
displacement control: $K_p=1000$ and $K_i=0.2$; resistance control: $K_p=4000$ and $K_i=0.2$

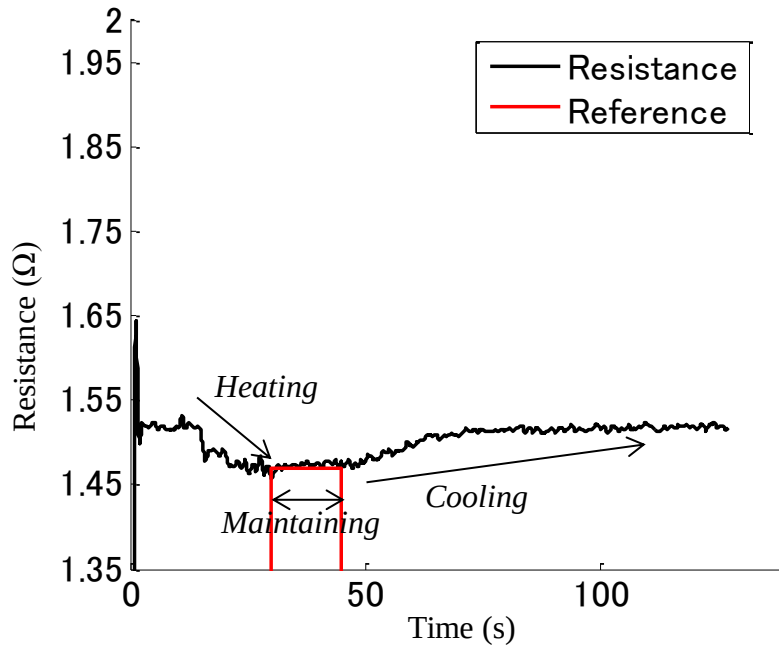


Fig. 5-12 Results of resistance for SMA1 with PRDFC in ambient temperature 24°C;
resistance control: $K_p=4000$, $K_i=0.2$

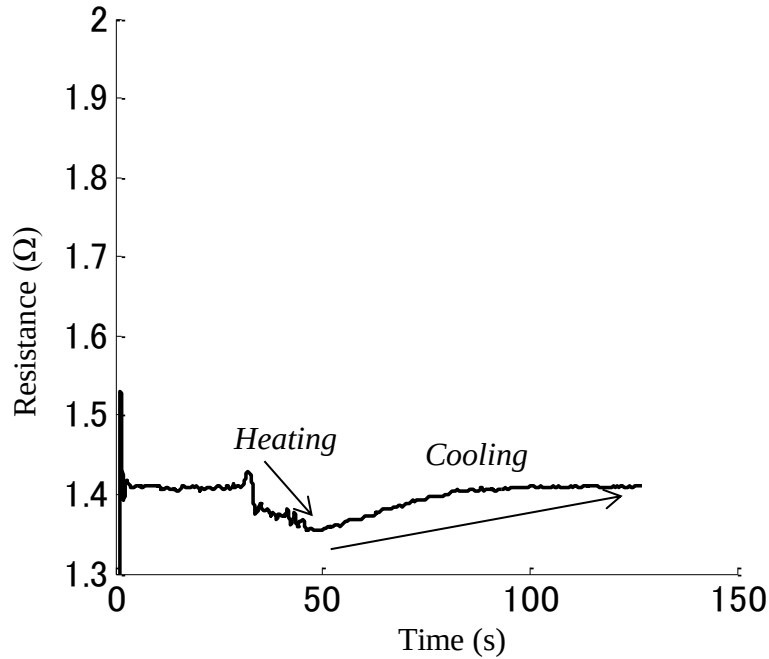


Fig. 5-13 Results of resistance for SMA2 with PRDFC in ambient temperature 24°C;
displacement control: $K_p=1000$ and $K_i=0.2$

Fig. 5-10 shows the results of resistance for SMA2. It also demonstrates the variation of resistance using displacement as feedback during heating process. When the power is turned off from 90s, the resistance increases quickly during the cooling process.

In addition, experiments are also conducted with ramp signal using the same PI controller as step as reference input to demonstrate the feasibility of the proposed method. Fig.5-11 shows the experimental results of the proposed PRDFC and traditional control with ramp signal. Part 1 and part 2 are used as displacement feedback for SMA1 and SMA2, respectively. The tracking trajectory of PRDFC is also the same as that of displacement feedback control plotted using the black line. It is observed that the proposed PRDFC behaves more rapid response speed than the traditional method during the cooling process from 45s to 130s as well. Since during tracking period of SMA2 from 30s to 45s, the latency duration of SMA1 is shortened, which leads to rapid

cooling speed during the cooling process from 45s when the power is turned off. And the traditional method leads to more latency duration ($T_{cd}=6s$) than proposed method. According to criteria to decide the martensite finish time with horizontal line mentioned in 3.5 as well, the proposed and traditional method complete the cooling process at $e=108s$ and $f=120s$, respectively.

Fig. 5-12 and Fig. 5-13 show the results of resistance with PRDFC. In Fig.5-12, the resistance of SMA1 decreases from 10 s since the displacement is used as feedback from 10s to 30s. During this heating process, the SMA1 completes the transformation from martensite to austenite. From 30s to 45s, the resistance of SMA1 is maintained at R_{ms} , which makes the output displacement unchangeable during the maintaining period to actuate SMA2 using the displacement as feedback because the SMA2 will not be interfered by the output displacement of SMA1. During maintaining process, the SMA1 completes the transformation from austenite finish phase to martensite start phase which leads to a shortening latency duration T_{cd} .

5.5 Consideration and Discussion

The proposed method demonstrates more rapid response speed than traditional displacement feedback control. There are, however, a few critical points needing further consideration.

1. As shown in Fig. 5-9 and Fig. 5-11, both the step and ramp signals show that the proposed method lead to more rapid response speed than traditional displacement feedback control because the proposed method shortens the latency duration T_{cd} of SMA1 which is caused by the hysteresis effect. However, as mentioned in

section 4.5, there is still latency duration T_{Lp} which can not be eliminated totally. In addition, the parameters of tuning PI controller is important since the best and similar position tracking can eliminate the possibility that the rapid speed of proposed method arises from other factors. Another limitation is only the latency duration of SMA1 is shortened in these tests even though two SMA wires are used in the experiments.

2. As shown in Fig. 5-9 and Fig. 5-11, the speed of heating process with traditional method for step input 0.8mm is faster than with the proposed method. Because the SMA length for the traditional method is 280 mm, however, the SMA length for the proposed method is 140mm for part 1. With the same PID parameter and reference input, the maximum output displacement for the traditional method is larger than proposed method in part 1, resulting faster response speed during heating process. Since the remaining maximum output displacement of both methods is the same for the part 2, say 0.71mm, the speed of heating process is almost the same.
3. Concerning about PRDFC, it is important to make two SMA wires output displacement continuously. Once there is no output displacement from SMA1, SMA2 should be actuated quickly. The part ϕ caused by thermal expansion of SMA2 (Fig. 5-11) leads to less accurate for the position tracking control compared with tradition method. In addition, it is important to distinguish the maximum output displacement of SMA wire to avoid overheating with PRDFC. A maximum ramp signal, 1.6mm(1.0mm for SMA1, 0.6mm for SMA2), is used as reference input to verify this statement. As shown in Fig. 5-14, part 1 and part 2 are used as displacement feedback for SMA1 and SMA2, respectively. When

the maximum reference input for the SMA1 is 1.0mm, but the maximum output for SMA1 is only $m=0.8\text{mm}$ (0.01mm offset from the maximum output displacement 0.81mm), then SMA1 will be over heated from m to n , which leads to more overshoot and undershoot than traditional method from 30s to 40s.

4. As shown in Fig. 5-9 and Fig. 5-11, the maximum offset for the output displacement is respective 0.06mm and -0.07mm when SMA finishes the transformation from austenite to martensite during the cooling process at f and e , which is arisen from the same reason mentioned in section 4.5.

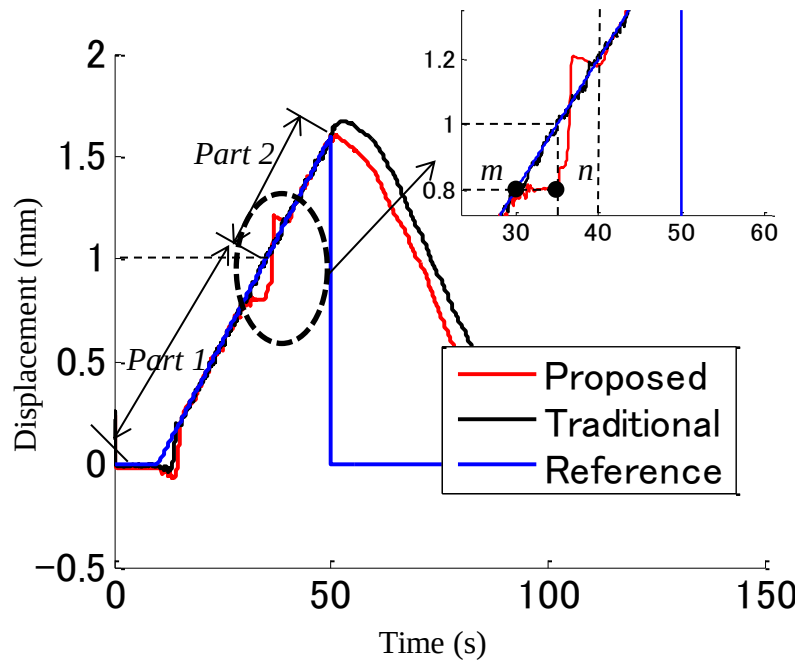


Fig. 5-14 Results of overheating for SMA1 in ambient temperature 24°C;
displacement control: $K_p=1000$ and $K_i=0.2$; resistance control: $K_p=4000$ and $K_i=0.2$

5.6 Chapter Summary

An SMA actuator structure and control system using two connected SMA wires which is able to generate rapid response for thick SMA actuators is proposed. Two sets of signal are used as reference input to test the results of both proposed and traditional method. The results show that using only displacement as feedback leads to slower cooling speeds than with the proposed PRDFC.

Since experiments demonstrated that the thick SMA wires suffer from significant hysteresis effects with long latency duration (chapter 3), to obtain a rapid response of the SMA actuators, this chapter proposes a PRDFC (Phase resistance with displacement feedback control) method using the concept of phase transformation resistances that dividing the hysteresis loop into four parts (chapter 4).

In the experiments, SMA1 is used in the position tracking control with displacement as feedback first. Then SMA2 is used in the position tracking control when SMA1 is maintained using resistance as feedback. This enables a shortening of the latency duration with two connected SMA wires coordinated by using the phase resistance and displacement as feedback when compared with the case where only displacement feedback is used.

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CHAPTER 6:

MODELING OF AN SMA ACTUATOR BASED ON THE LIANG AND ROGERS MODEL

6.1 Introduction

In modeling the hysteresis of an SMA to accurately estimate the behavior of the SMA actuator, many models have been proposed during the last decade. However, the main difficulty in modeling SMA actuators is due to the non-linear saturated hysteresis effect during the phase transformation from martensite to austenite, or vice-versa. Hirose, Ikuta and Umetani proposed a two-phase model for SMA using the sub-layer model, a commonly used method to describe nonlinear stress-strain relationships in solid mechanics [86]. Tanaka developed a thermo-mechanical law that governs the stress-strain behavior of SMA elements [30]. Williams and Mohammad introduced a model of an SMA actuator which consists of four sub-models: a heat transfer model, an SMA thermo-mechanical model, a phase transformation kinetics model, and a dynamic/kinematic model [87]. However, these models did not show the minor hysteresis relationship between input and output even though they can precisely reproduce the thermo-mechanical behavior of SMA. Dutta and Ghorbel proposed a model using a differential hysteresis model capable of representing the major and minor hysteresis loops [38]. However, this model can not show the relationship between martensite start temperature and the maximum temperature during heating process of each minor hysteresis loop. In this chapter, the motivations will first be explained. In

section 6.3 and 6.4, the method and results will be described. Some discussions and conclusions will be shown in section 6.5 and 6.6.

6.2 Motivation and Target

In this chapter, a successful empirical relation proposed by Liang and Rogers is introduced in order to model the major hysteresis behaviors of SMA actuators, which represents the amount of austenite fraction transformed on a temperature [34]. Liang and Rogers described a unified, thermomechanical constitutive model to quantitatively predict the stress-strain relation and shape memory behavior. It also focused on shape memory effects and provided a theoretical guide to the design of SMA based on intelligent material and structures. However, it is difficult to apply the method to practical application without representing the minor hysteresis loops, successfully. Based on the empirical relation of the Liang and Rogers model, a modified Liang and Rogers model is demonstrated to consider the major and minor hysteresis behaviors. An experimental setup used for verification of the modeling system is presented and some test series are conducted to identify the parameters of the modified Liang and Rogers model. The reasonable agreement achieved between curves predicted by the modified Liang and Rogers model and the measured data shows that the proposed model is efficient in modeling the hysteresis of the SMA actuator system.

6.3 Method

6.3.1 Thermal Model of Heat Transfer and Temperature

As mentioned in chapter 2, an SMA returns to some predefined shape or size when

subjected to an appropriate thermal procedure, and is known as a shape memory effect. The shape memory effect arises from temperature and stress dependent shifts in the crystalline structure of the SMA, shifts between martensite and austenite phases. The system gains heat energy from an electrical current, and loses part of it to the environment. As suggested in Fig. 6-1, this model considers an SMA element as a three-element system in which thermal energy is converted into a phase transformation and then into mechanical work. In this section, a new mathematical model of the SMA actuator is introduced, including the major and minor hysteresis loops to model the transformation model of SMA actuator.

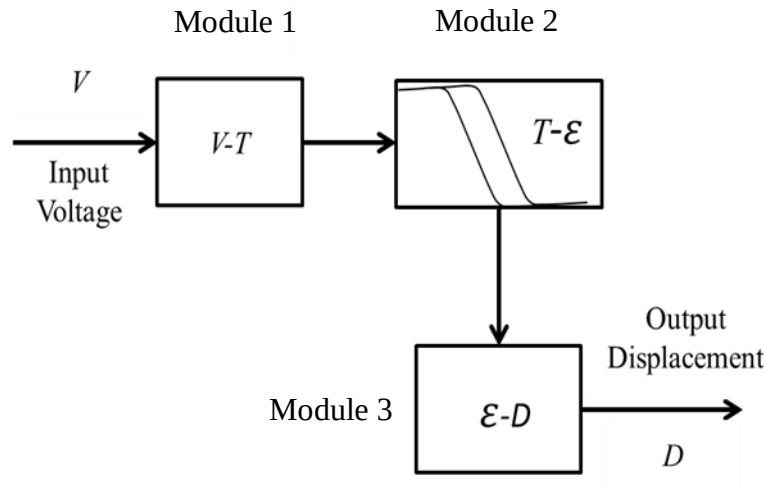


Fig. 6-1 Block diagram model of SMA

In this section, the heat transfer problem of the SMA wire is described. The balance of the heat energy governs the temperature of the SMA actuator. For a spring-biased SMA wire, the thermal model between input voltage v and the output temperature T , which is shown in module 1 (Fig. 6-1), is a first-order system given by

$$\rho \cdot c \frac{\pi d_0^2 L_0}{4} \cdot \frac{dT}{dt} = \frac{V^2(t)}{R} - \pi d_0 L_0 h(T - T_{amb}) \quad (6-1)$$

where ρ is the density of the SMA; c is the specific heat coefficient; L_0 is the length of the SMA wire; d_0 is cross-sectional diameter of the SMA; V is the voltage applied; R is the resistance; h is the convection heat transfer coefficient, and T_{amb} is the ambient temperature.

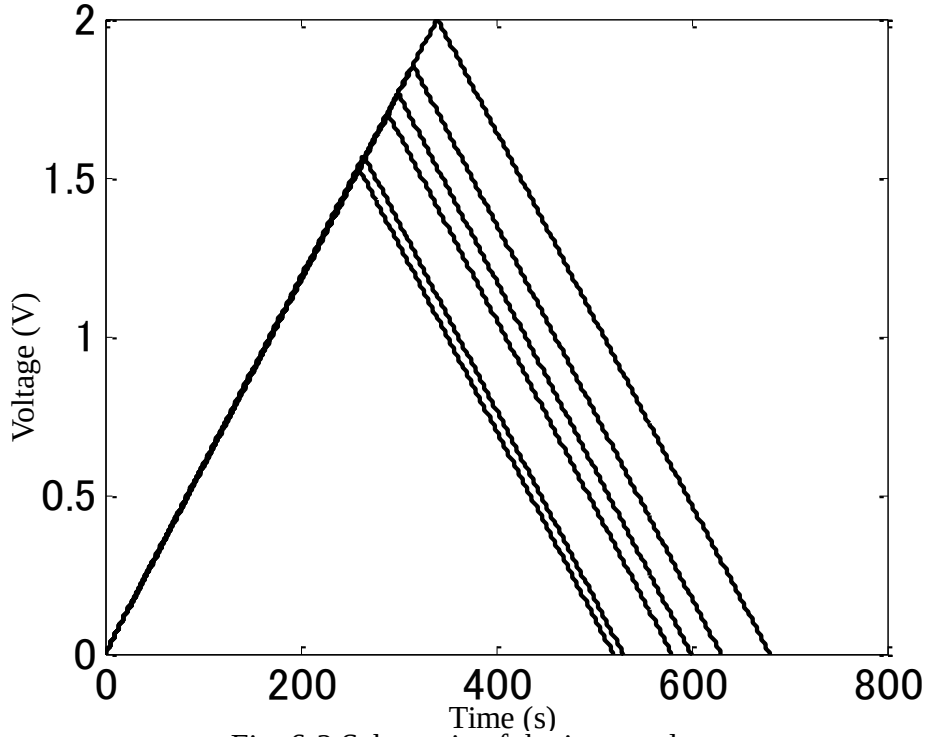


Fig. 6-2 Schematic of the input voltage

Since the actual temperature of the SMA wire is not measured in the experiments, direct validation of the heat transfer model mentioned above is not possible. However, the simulation result is able to demonstrate the thermal transfer model. Fig. 6-2 shows that six triangular voltages are set as the input voltage for simulation. The maximum of input voltage is 2V for the major loop and the others are for the minor loops. Fig. 6-3 shows the simulation results of the output temperature obtained from Eq. (6-1) corresponding to the input voltage shown in Fig. 6-2.

6.3.2 Phase Transformation and Mechanical Model

During the heating process, a phase transformation occurs from martensite to austenite, while during the cooling process, the opposite transformation occurs, and SMA wires show a hysteresis effect during both phase transformations. The extent of austenite to martensite transformation is characterized by the martensite fraction ε_m . Martensite fraction is defined as the volume fraction of M phase present in the SMA at any instant. Therefore, $0 \leq \varepsilon_m \leq 1$. As shown in Fig. 6-4, the transformation is characterized by the initial and finish temperatures. T_{MS} and T_{MF} are the initial and final temperatures of martensite, while T_{AS} and T_{AF} are the initial and final temperatures of austenite, respectively.

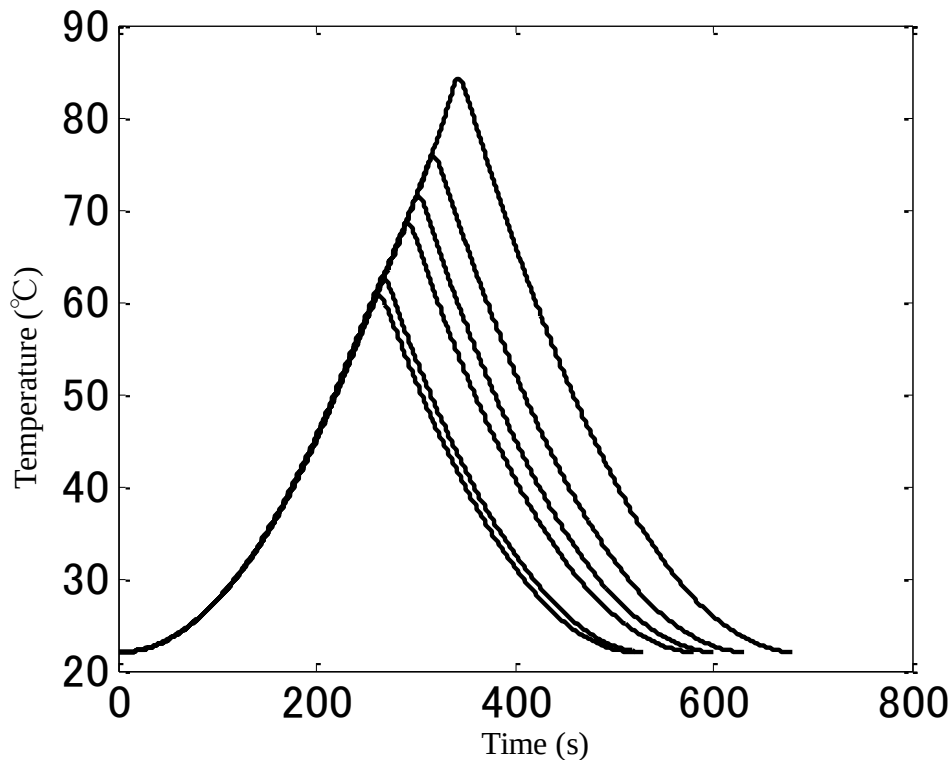


Fig. 6-3 Schematic of the output temperature

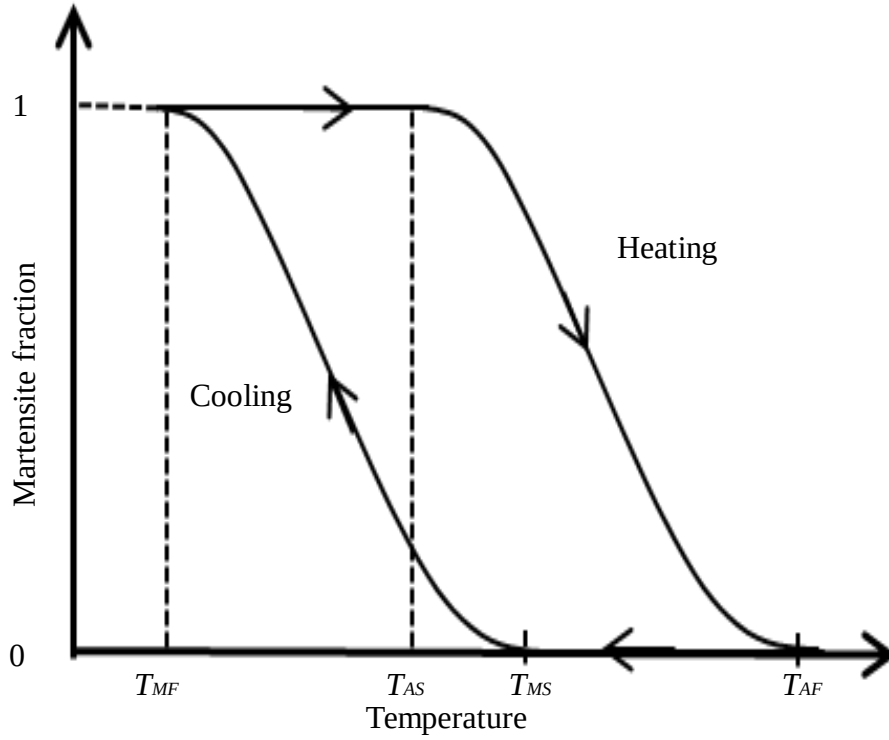


Fig. 6-4 Schematic of martensite fraction-temperature hysteresis

The classical Liang and Rogers model uses trigonometric functions to characterize the hysteresis effect of module 2 for the SMA actuators. During the heating and cooling processes, the functions of the martensite fraction ε_{mh} and ε_{mc} are expressed by

$$\varepsilon_{mh} = \begin{cases} 1 & T < M_1 \\ 0.5 \left[1 + \cos \pi \left(\frac{T - T_{AS}}{T_{AF} - T_{AS}} \frac{F}{A \cdot C_A} \right) \right] & M_1 \leq T \leq M_2 \quad (\text{Heating}) \\ 0 & T > M_2 \end{cases} \quad (6-2)$$

$$\varepsilon_{mc} = \begin{cases} 1 & T < M_3 \\ 0.5 \left[1 + \cos \pi \left(\frac{T - T_{MF}}{T_{MS} - T_{MF}} \frac{F}{A \cdot C_M} \right) \right] & M_3 \leq T \leq M_4 \\ 0 & T > M_4 \end{cases} \quad (\text{Cooling}) \quad (6-3)$$

where $M_1 = T_{AS} + F/(A \cdot C_A)$; $M_2 = T_{AF} + F/(A \cdot C_A)$, $M_3 = T_{MF} + F/(A \cdot C_M)$; $M_4 = T_{MS} + F/(A \cdot C_M)$; T is the temperature of the SMA wire; F is the pre-tension; A is the cross section area of the wire; C_M is the stress rate of martensite, and C_A is the stress rate of austenite.

Then the austenite fractions during the heating and cooling processes can be defined as $\varepsilon_{ah} = 1 - \varepsilon_{mh}$ and $\varepsilon_{ac} = 1 - \varepsilon_{mc}$, respectively. Since the effect of pre-tension is small in the experiments, the equations proposed by Liang and Rogers that model such transformations as function of temperature are simplified as

$$\varepsilon_{ah} = \begin{cases} 1 & T > T_{AF} \\ 0.5 \left[1 - \cos \pi \left(\frac{T - T_{AS}}{T_{AF} - T_{AS}} \right) \right] & T_{AS} \leq T \leq T_{AF} \\ 0 & T < T_{AS} \end{cases} \quad (\text{Heating}) \quad (6-4)$$

$$\varepsilon_{ac} = \begin{cases} 1 & T > T_{MS} \\ 0.5 \left[1 - \cos \pi \left(\frac{T - T_{MF}}{T_{MS} - T_{MF}} \right) \right] & T_{MF} \leq T \leq T_{MS} \\ 0 & T < T_{MF} \end{cases} \quad (\text{Cooling}) \quad (6-5)$$

where ε_{ah} and ε_{ac} are the amount of austenite fractions during the heating and cooling processes, respectively.

However, the Liang and Rogers model only represents the major hysteresis loop of

phase transformation without considering the martensite starting temperature of minor loops. A typical austenite fraction-temperature hysteresis schematic is shown in Fig. 6-5 [38]. The hysteresis loop corresponding to complete phase transformation is called the major hysteresis loop, while incomplete phase transformation yields minor hysteresis loops within the major hysteresis loop. The martensite starting temperature of each minor loop is the same value as the major loop [38].

According to the experimental data described in section 6.4, the minor hysteresis loops can be revised in a new shape shown in Fig. 6-6. The martensite starting temperature of each minor loop is different. The solid line represents the major hysteresis loop and the dashed lines are for the minor loops. Since the transformation temperature variation caused by the applied stress is small in this experiment, we assume that the phase transformation temperatures are constant throughout for major and minor hysteresis loops.

If $T_i \leq T_{AS}$, then $\varepsilon_{ahi}(T)=0$, and therefore, only the case of $T_i > T_{AS}$ is considered.

For a hysteresis loop, the austenite fraction ε_{ahi} during the heating process is expressed by

$$\varepsilon_{ahi}(T) = \begin{cases} 1 & T \geq T_i > T_{AF} \\ 0.5 \left[1 - \cos \pi \left(\frac{T - T_{AS}}{T_{AF} - T_{AS}} \right) \right] & T_{AS} \leq T < T_i \leq T_{AF} \\ 0 & T \leq T_i < T_{AS} \end{cases} \quad (i=1,2,\dots,N) \quad (6-6)$$

where $i=1,2,3,\dots,N$; T_i is the maximum temperature during the heating process of a hysteresis loop, including minor hysteresis loops. However, Eq. (6-6) is derived from Eq. (6-4) without modified minor hysteresis loops of heating process.

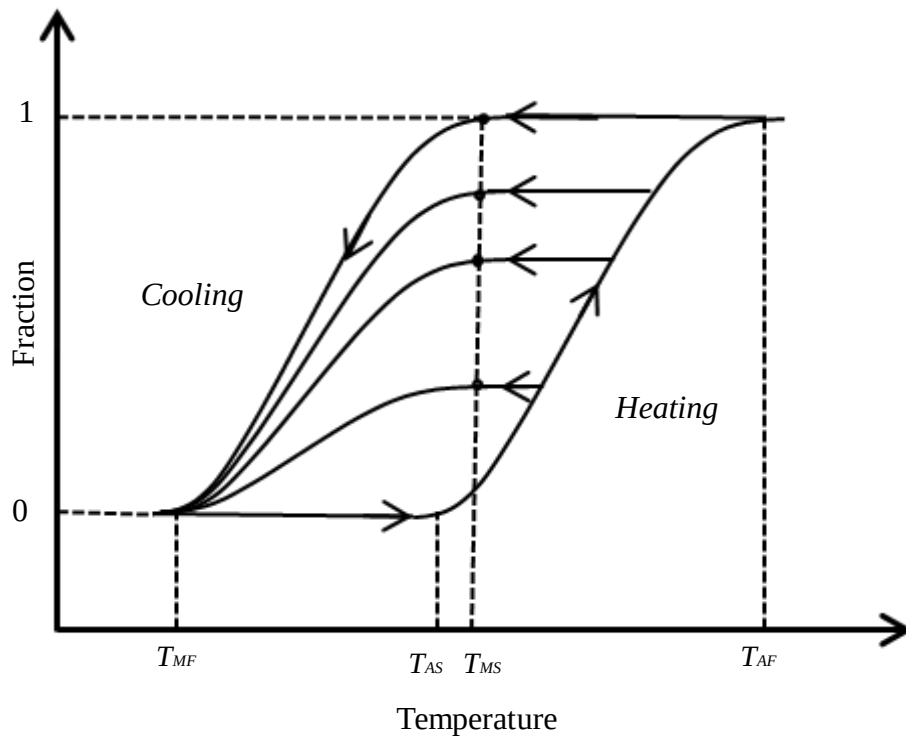


Fig. 6-5 Schematic of typical austenite fraction-temperature hysteresis

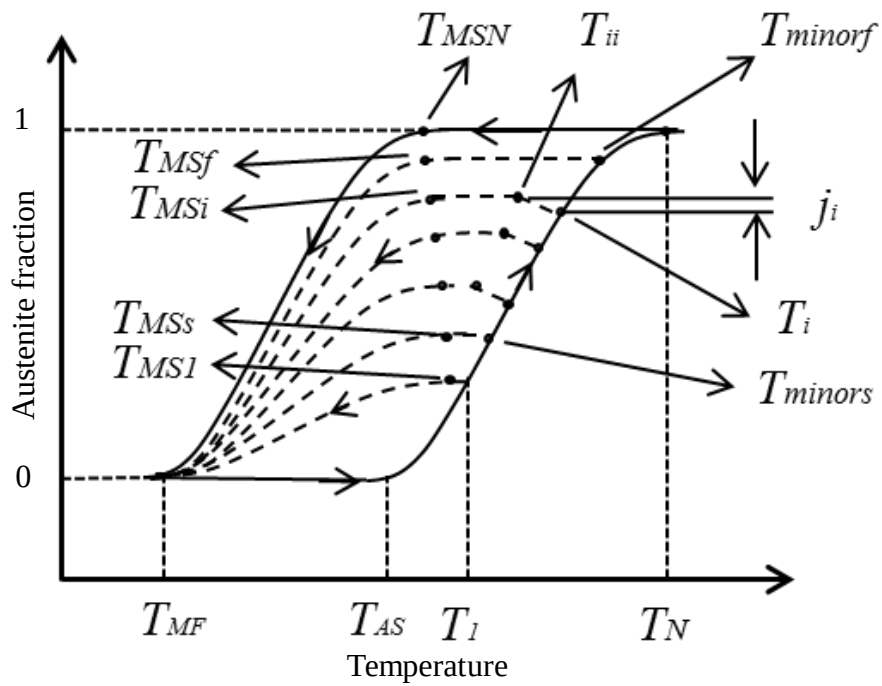


Fig. 6-6 Schematic of austenite fraction-temperature hysteresis with modification

When $T_{\text{minors}} < T_i < T_{\text{minorf}}$, then the austenite fraction increases first, and is maintained unchanged, then decreases during the cooling process; the equation of the increase and maintaining stages ε_{acii} is expressed by

$$\varepsilon_{acii}(T) = \begin{cases} \varepsilon_{ahi}(T_i) + z_i(T) & T_{ii} < T < T_i \quad \text{increase} \\ \varepsilon_{ahi}(T_i) + z_i(T_{ii}) & T_{MSi} \leq T \leq T_{ii} \quad \text{maintaining} \end{cases} \quad (6-7)$$

where T_{ii} is the starting temperature of the maintaining stage and can be expressed by

$$T_{ii} = NT_{ii}(T_{\text{max } ii} - T_{\text{min } ii}) + T_{\text{min } ii}, \quad T_{\text{min } ii} \leq T_{ii} \leq T_{\text{max } ii} \quad (6-8)$$

where $T_{\text{max } ii}$ and $T_{\text{min } ii}$ are the maximum and minimum of T_{ii} . NT_{ii} can be expressed by

$$NT_{ii} = a_5 NT_i^5 + a_4 NT_i^4 + a_3 NT_i^3 + a_2 NT_i^2 + a_1 NT_i^1 + a_0 \quad (6-9)$$

where NT_i can be expressed by

$$NT_i = \frac{T_i - T_{\text{minors}}}{T_{\text{minorf}} - T_{\text{minors}}}, \quad T_{\text{minors}} \leq T_i \leq T_{\text{minorf}} \quad (6-10)$$

where T_{minors} and T_{minorf} is the starting and finishing temperature with increase stages of cooling process, respectively. T_{MSi} is the martensite starting temperature of a minor hysteresis loop; $z_i(T)$ is defined as the function for the cooling process in the minor hysteresis loop.

In order to make sure $0 \leq \varepsilon_{acii}(T) \leq 1$ and simplify the equation of $z_i(T)$, the temperature is normalized. $z_i(T)$ can be expressed by

$$z_i(T) = \begin{cases} \frac{j_i(T_i - T)}{T_i - T_{ii}} & T_{ii} < T < T_i \\ z_i(T_{ii}) = j_i & T_{MSi} \leq T \leq T_{ii} \end{cases} \quad (6-11)$$

where j_i is the constant for a minor hysteresis loop.

The martensite starting temperature T_{MSi} , which must be determined to model minor hysteresis loop, is expressed by

$$T_{MSi} = NT_{MSi}(T_{minorf} - T_{minors}) + T_{minors}, \quad T_{minors} \leq T_i \leq T_{minorf} \quad (6-12)$$

where the normalized resistance NT_{MSi} is expressed by

$$NT_{MSi} = m_4 NT_i^4 + m_3 NT_i^3 + m_2 NT_i^2 + m_1 NT_i^1 + m_0 \quad (6-13)$$

where m_4, m_3, m_2, m_1 and m_0 are the parameters obtained by polyfit of Matlab.

When $T_1 < T_i \leq T_{minors}$ and $T_{minorf} \leq T_i < T_N$, then $z_i(T) = 0$, there are only maintaining stages. Therefore, the martensite starting temperature T_{MSi} can be expressed by

$$T_{MSi} = q \varepsilon_{ahi}(T_i) + e \quad (6-14)$$

where q and e are the constants.

During the cooling process, the austenite fraction for a loop can be expressed by

$$\varepsilon_{aci}(T) = \begin{cases} \varepsilon_{acii}(T) & T_i \geq T > T_{MSi} \\ 0.5 \left[1 - \cos \pi \left(\frac{T - T_{MF}}{T_{MSi} - T_{MF}} \right) \right] \varepsilon_{acii}(T_{MSi}) & T_{MF} \leq T \leq T_{MSi} \\ 0 & T < T_{MF} \end{cases} \quad (6-15)$$

For the mechanical model, the module 3 (Fig. 6-1) shows the output displacement D , which combines the thermal model and phase transformation model developed above, is

expressed by

$$D = \begin{cases} g \varepsilon_{ahi} & \text{heating} \\ g \varepsilon_{aci} & \text{cooling} \end{cases} \quad (6-16)$$

where g is constant parameter.

With the three models mentioned above, the hysteresis loops of input voltage and output displacement including the major and minor loops can be plotted. The parameters of each loop can be obtained according to the experimental results which will be presented in the following.

6.4 Results

The experimental setup of the proposed SMA actuator was the same as Fig. 3-5 in chapter 3. The parameters of the experiments are listed in Table 6-1. To accurately identify the parameters of the modified Liang and Rogers model formulated for modeling the saturated hysteresis nonlinearity of an SMA actuator, the input voltage applied to the SMA actuator in the training process is a slow decaying ramp signal, making it possible to allow the temperature to stabilize, as in the steady state the temperature will be decided by the applied voltage [62]. As shown in Fig. 6-7, the slopes of the decay reversal curves are set to $\pm 5.88 \times 10^{-3}$ in the training process of the modified Liang and Rogers model, including the maximum and minimum at 2.35V and 1.47V, respectively. Fig. 6-8 shows the results of the experiments with input voltage-output displacement hysteresis loops for the SMA actuator using the input voltage in Fig. 6-7. When the input voltage is below 1.47V or above 1.88V, the minor hysteresis loops can be expressed by the modified Liang and Rogers model without the

increase stage. However, minor loops with input voltage V_{input} , $1.47V < V_{input} < 1.88V$, where small changes in the input voltage lead to considerable displacement changes, need to be expressed by the modified Liang and Rogers model with the increase stage.

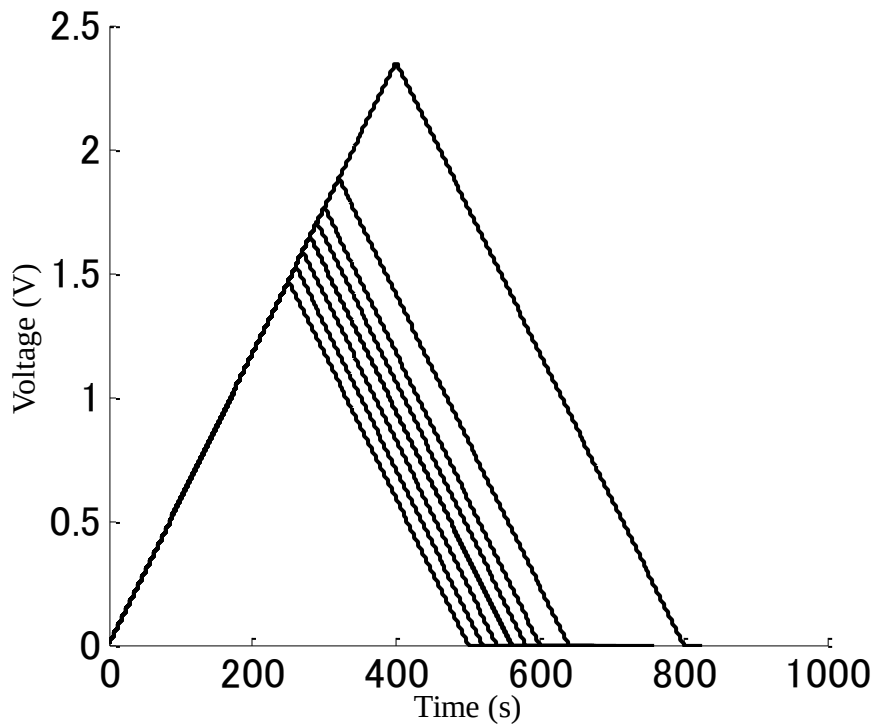


Fig. 6-7 Schematic of the input voltage

Table 6-1 Parameters of the experiments

Ambient temperature	22°C	SMA diameter	0.5mm
MOSFET	K2232	SMA length	140mm
Power supply	5V	Spring stiffness	653.3N/m
Microcontroller	Arduino	Pretension force	2.75N

Then, parameter identification for the proposed model, simulation results by the proposed model, and a comparison with the experimental data are presented. Estimates for parameters used in Eq. (6-13) and Eq. (6-14) are obtained by curve fitting. The remaining parameters are identified using the actual displacement measured by the laser sensor, as actual temperature measurements are not available.

Based on Eq. (6-6) and Eq. (6-15), Fig. 6-9 shows the results of simulated austenite fraction versus time, including the major and minor hysteresis loops of the SMA actuator. The six modified Liang and Rogers model parameters are listed in Table 6-2. T_{minors} , T_2 , T_3 , T_4 , and T_{minorf} are selected to identify the parameters in Eq. (6-10), (6-12), (6-13), while T_{minors} , T_{minorf} , and T_{AF} are for the parameters in Eq. (6-14). The corresponding major and minor loops of austenite fraction versus temperature are shown in Fig. 6-10. It is evident that the hysteresis loops in Fig. 6-6 would qualitatively match the hysteresis loops in Fig. 6-10. To obtain the martensite starting temperature T_{MSi} , Fig. 6-11 and Fig. 6-12 show the simulation results of T_{MSi} based on the Eq. (6-13) and Eq. (6-14), respectively. The results show that the martensite starting temperature T_{MSi} can be predicted.

With the relationship between input voltage and output temperature in Eq. (6-1) of module 1, the input temperature and output austenite fraction in Eq. (6-6) and (6-15) of module 2, the input austenite fraction and output displacement in Eq. (6-16) of module 3, as shown in Fig. 6-13, the input voltage VS output displacement with the modified Liang and Rogers model is plotted, including the major loop plotted in a solid line and the minor loops plotted in dashed lines.

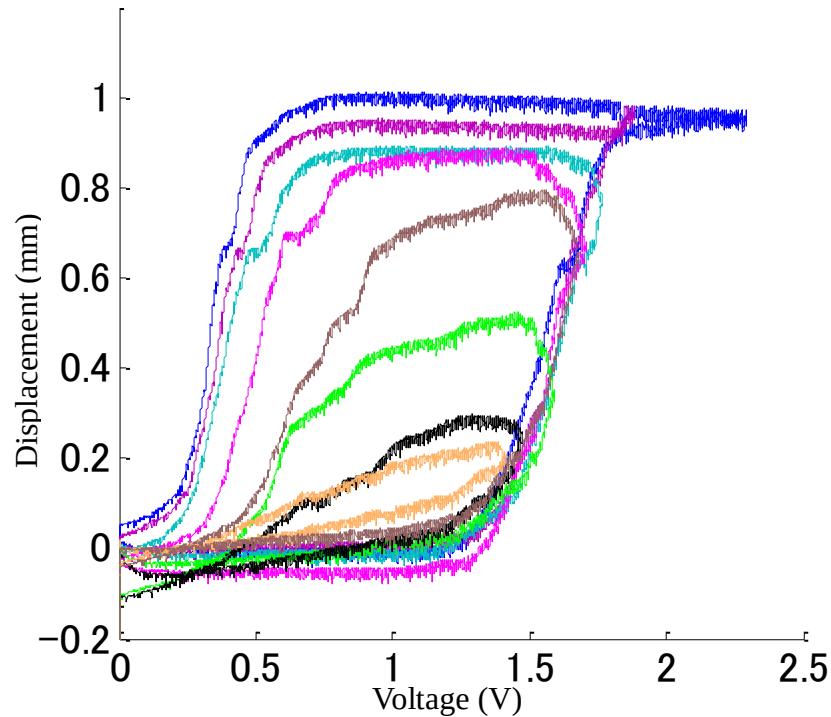


Fig. 6-8 Schematic of the displacement VS input voltage

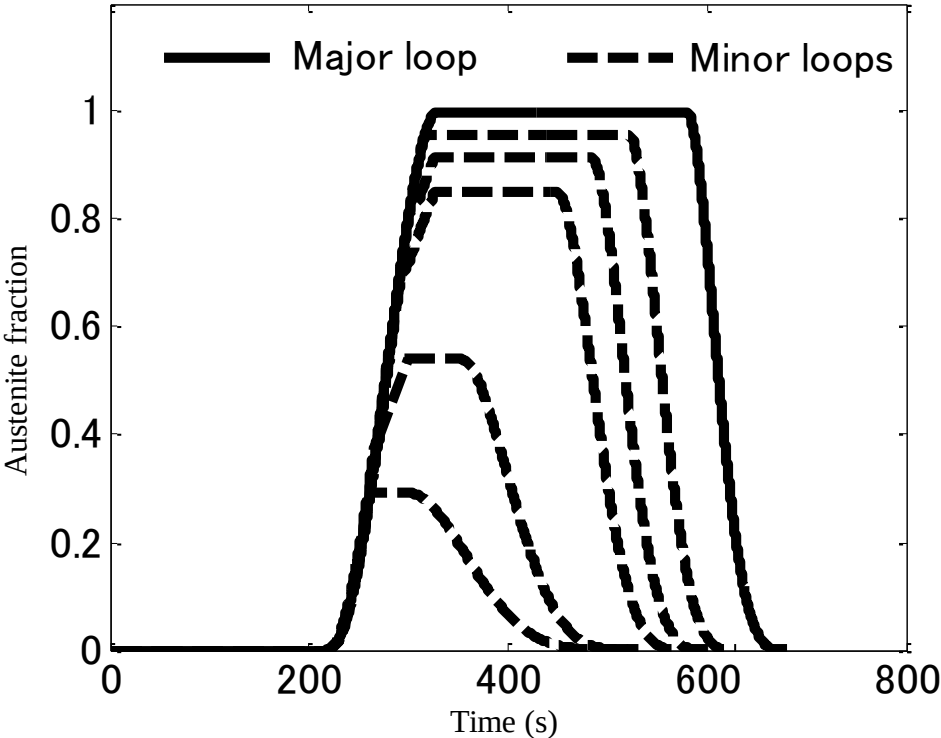


Fig. 6-9 Simulated austenite fraction versus time

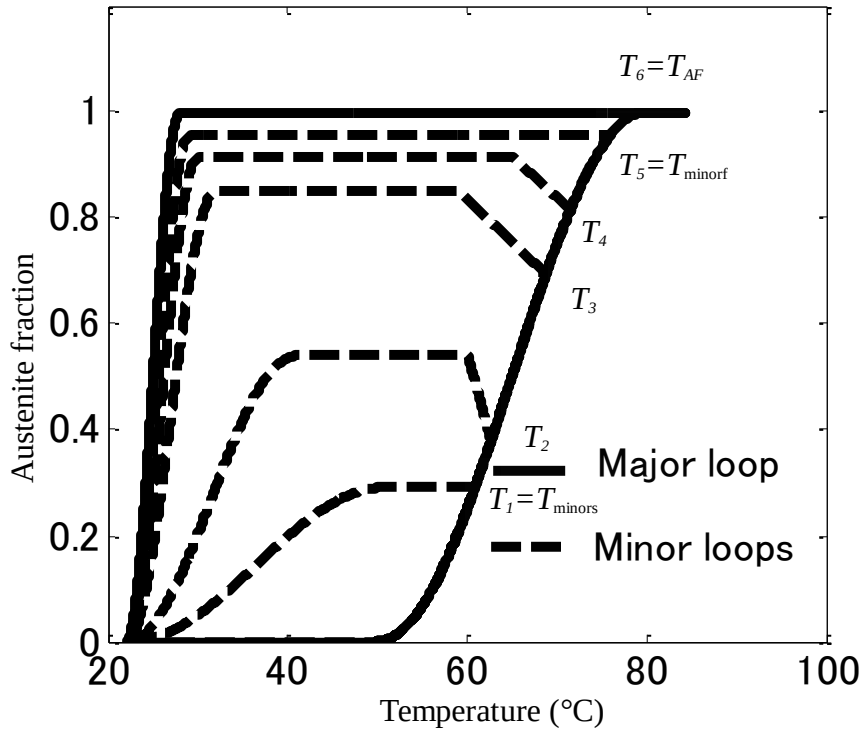


Fig. 6-10 Simulated austenite fraction versus temperature

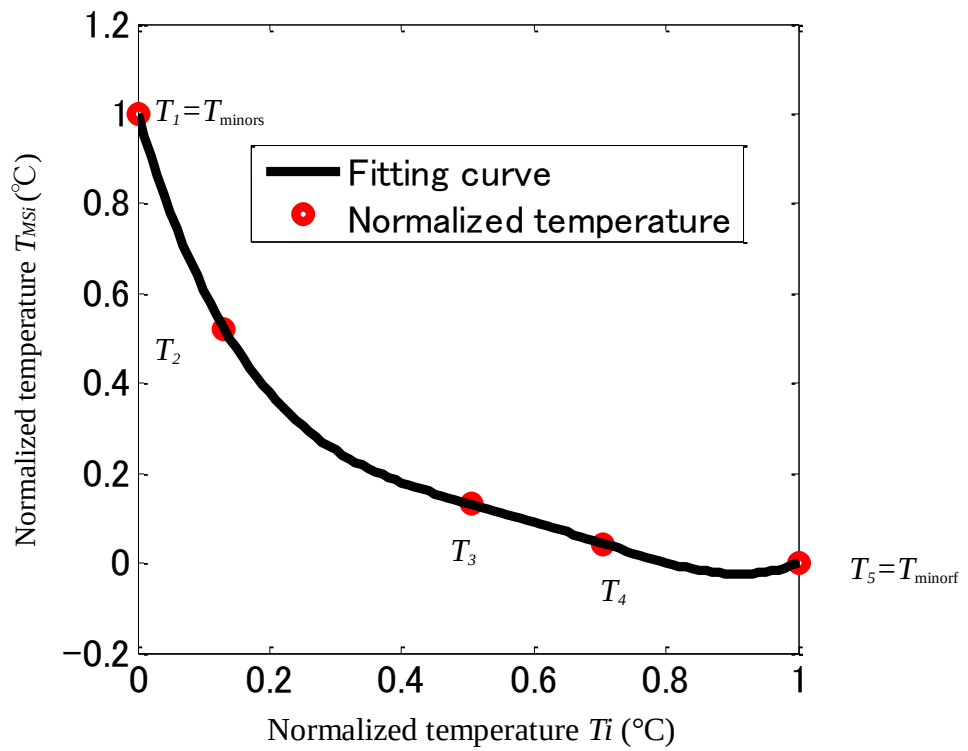


Fig. 6-11 Curve for fitting the normalized martensite starting temperature

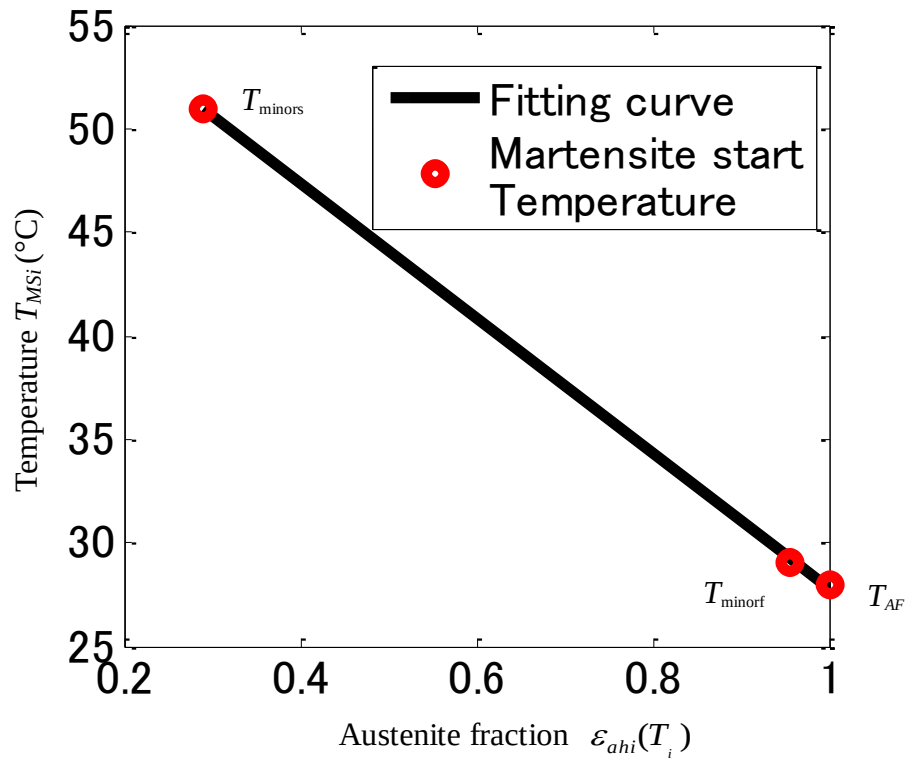


Fig. 6-12 Curve for fitting the martensite starting temperature

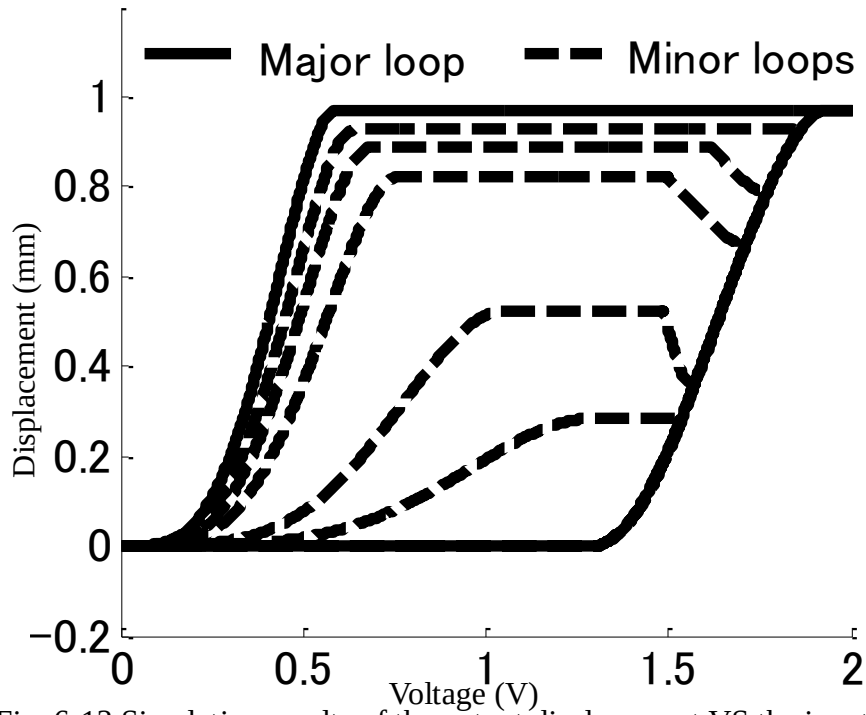


Fig. 6-13 Simulation results of the output displacement VS the input voltage

Table 6-2 Simulation parameters

Parameter	Value	Parameter	Value
ρ	6500kgm ³	R	1 Ω
h	165W/m ² °C	c	836.8 J/kg°C
q	-32.69	e	60.47
T_{AS}	50.2°C	T_{AF}	80.1°C
T_{MS}	28°C	T_{MF}	22°C
T_{MSf}	28.9°C	T_{MSs}	51.1°C
$\dot{j}_f$	0	$\dot{j}_s$	0
ε_{ahf}	0.96	ε_{ahs}	0.29
T_f	75.9°C	T_s	60.8°C
T_{MS2}	40.8°C	T_{MS3}	32.1°C
$\dot{j}_2$	0.16	$\dot{j}_3$	0.19
ε_{ah2}	0.38	ε_{ah3}	0.66
T_2	63.1°C	T_3	68.5°C
T_{22}	61.2°C	T_{33}	59.1°C
T_{MS4}	30.1°C	T_4	71.5°C
$\dot{j}_4$	0.1	T_{44}	65.2°C
ε_{ah4}	0.82	g	0.96
m_4	5.24	m_3	-12.80
m_2	11.50	m_1	-4.94
m_0	1.00		

6.5 Consideration and Discussion

As shown in Fig. 6-14, the output with the modified Liang and Rogers model is plotted together with the experimental data (colors other than red), with the major loop plotted in a red solid line and the minor loops plotted in red dashed lines. This figure clearly shows that the modified Liang and Rogers model can effectively characterize the hysteresis behavior of the SMA actuator. However, there are some factors needed to be discussed.

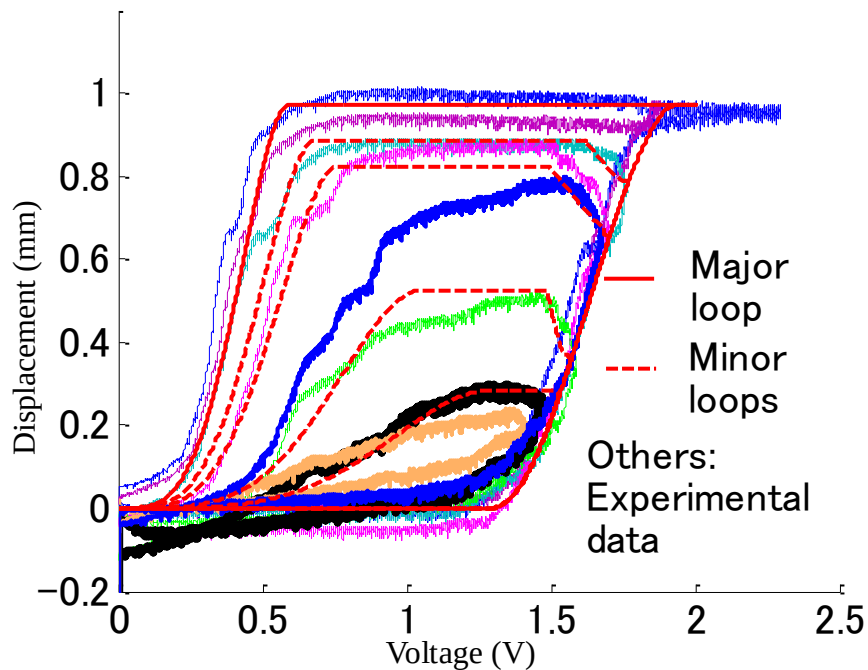


Fig. 6-14 Plot with experimental and simulated data
by the modified Liang and Rogers model

1. The Liang and Rogers model has found widespread use in SMA modeling and position control, but the limitation has been mentioned above which the temperature of SMA wire needs to be measured to decide the martensite and

austenite phase. As shown in Fig. 6-13, the proposed model does not suffer from this limitation since the simulation results show the relationship between input voltage and output displacement. Concerning about the simulation and experimental results, as shown in Fig. 6-14, six models are built to model the basic shape of the hysteresis loops including major and minor loops. However, the parameters (Table 6-2) of the model need to be changed once the ambient conditions changed. For example, the variation of bias force leads to a shift of the hysteresis. An increase in force causes a shift to the right, a decrease shifts the hysteresis to the left [81], which leads to modify the parameters to fit the experimental data. Therefore, it is difficult to use this model in unstable environment.

2. As shown in Fig. 6-14, the discrepancy between the simulated and experimental data can be explained as follows. The measured displacement shown in Fig. 6-8 corresponds to the voltage profile in Fig. 6-7. Thus, the output displacement should be smooth. However, due to the ambient conditions of the experimental setup are not constant over time and space, the error is unavoidable.
3. As shown in Fig. 6-8, the results of output displacement-voltage can repeat during the heating process including the major and minor loops. However results during the cooling process are different with since the martensite start temperature of each loop is different. It is evident that the SMA actuator behavior is highly nonlinear due to the complex physics.

6.6 Chapter Summary

In this chapter, a complete mathematical model for a spring-biased SMA actuator is proposed, including both the major and minor hysteresis loops. With the difference from reference [38] (Fig. 6-5), the proposed model is capable of simulating the temperature (especially about the martensite start temperature of each loop), austenite fraction and the output displacement of the actuator.

Based on the Liang and Rogers model, the modified Liang and Rogers model including the major and minor hysteresis loops is developed and the model parameters are adjusted by means of experimental identification procedure. The simulation results show that good accuracy of the model can be assured by using the modified Liang and Rogers model, including the increase and maintaining stages (expressed by Eq. (6-7)). The proposed model can predict the martensite starting temperature of the minor hysteresis loops, successfully.

Footnote: Junfeng Li, Hiroyuki Harada, Modeling of an SMA actuator based on the Liang and Rogers model, International Journal of Applied Electromagnetics Mechanics, Copyright (2013), accepted, with permission from IOS Press.

CHAPTER 7:

CONCLUSIONS AND FUTURE WORKS

7.1 Conclusions

In many applications where space, weight and noise can be an issue, SMA actuators present a potential solution with their high force-to-weight ratio, mechanical compactness, ease of miniaturisation, as well as their clean and silent operation. With improved speed, accuracy and controllability, the possibilities of using SMA actuators in, to name a few, robotics, consumer appliances and bio-medical applications, are greater now. In this thesis, the research focuses on achieving rapid control of SMA actuators and the obtained results are documented and discussed. The main content of this thesis can be summarized in the following.

In chapter 1, the objective, approach and the outline of thesis are introduced.

In chapter 2, literature overview which discusses the past research is presented in this work, including modeling and control system design. Some research is verified by the experimental results successfully. In addition, many methods developed using cooling device, thin SMA wires and new actuator structures to achieve fast response speed are introduced.

In chapter 3, the latency duration of the SMA wire is investigated. Experimental results show that the latency duration affected by the ambient temperature, which is due to the hysteresis effect can be observed.

In chapter 4, according to the definition of phase temperatures, the concept of phase resistance is defined for the first time. Phase resistances used to divide the hysteresis

loop into four parts are applied to shorten the long latency duration of thick SMA wire. The proposed method, phase resistance feedback control (PRFC), is presented here. The critical aspect of the PRFC method is to shorten the total cooling time by controlling the phase resistances. Two SMA wires connected by an insulation joint to prevent short circuiting will cooperate with each other to verify the possibility of the proposed methods. In order to show the advantages of the proposed method, the experimental results are compared with the results of binary control. Since the latency duration of heating process is shorter than cooling process, only the cooling process is considered in the proposed method.

In chapter 5, phase resistance with displacement feedback control (PRDFC) is also discussed, which shows another way to achieve rapid response speed and results are compared with traditional displacement feedback control as well to demonstrate the advantages of PRDFC. The central element of PRDFC is to divide the reference input into two parts which are assigned to both SMA wires, separately. Since there is only one displacement sensor to detect the position of SMA actuator, it is important to make sure only one SMA wire shrinks or extends for each reference input part. In order to explain the concept more clearly, a step signal is used as reference input. Combining the heating and cooling processes of the two SMA wires, the latency durations of SMA wire is shortened with the proposed method. And the results with PRDFC using ramp signal also demonstrate that the proposed method achieves more rapid response speed than traditional displacement feedback control.

In chapter 6, the complete mathematical model for a spring-biased SMA actuator is proposed, including both the major and minor hysteresis loops. Based on the Liang and Rogers model, the modified Liang and Rogers model including the major and minor

hysteresis loops is developed and the model parameters are adjusted by means of experimental identification procedure.

To sum up, the research presented in this thesis represents a significant step forward for practical SMA actuator applications in the future. Substantial improvements in terms of speed of SMA actuator control have been made compared with the past work. All of these have been accomplished with free convection cooling and not in a temperature-controlled condition in speed and position control system.

7.2 Future Works

The present research is a step forward towards the aim of achieving rapid response speed control of SMA actuator, and remains some limitations and insufficiency. In the rapid response speed control system, the latency duration of SMA wire is short if the diameter is small which makes it difficult to use phase resistance as feedback to obtain rapid response speed by shortening the latency duration. For the concept of PRDFC method, good results are demonstrated by the experimental tests. It is possible to test this method using other different reference input, such as square wave.

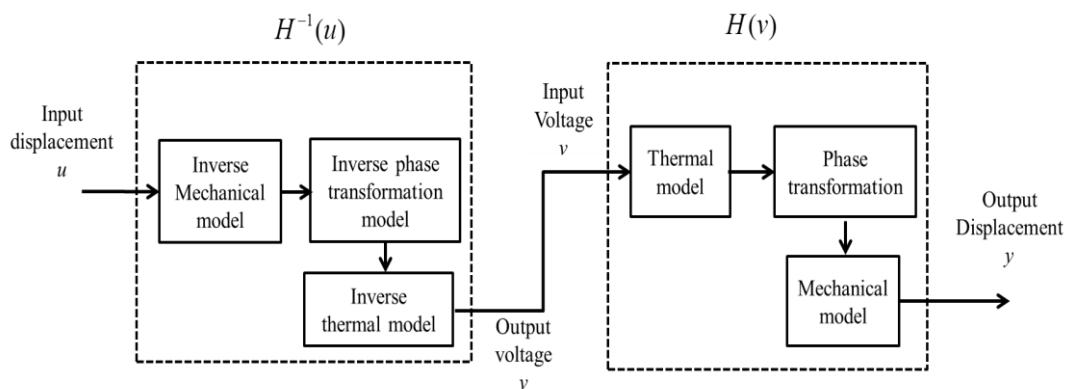


Fig. 7-1 Block diagram for the compensation based on the inverse model

Due to the hysteresis effect of SMA, it is difficult to control the SMA actuator. To completely compensate the hysteresis effect of an SMA system, it is important to develop the exact inverse of the hysteresis model. Generally, as suggested in Fig. 7-1, for the hysteresis model H and inverse model H^{-1} , the following equation can be developed if the inverse model exists [62].

$$y = H(v) = H(H^{-1}(u)) = u \quad (7-1)$$

here y is the output displacement of modified Liang and Roger model; v is the output voltage of the modified Liang and Roger inverse model which is used as the feedforward in the proposed control system; u is the input displacement.

ACKNOWLEDGEMENTS

There are many people who had made contributions, both directly and indirectly, towards the completion of this thesis. I would like to name a few. First and foremost, I would like to express my sincerest gratitude to my supervisor, Dr. Hiroyuki Harada. Harada sensei's help has been extremely enormous, and his enthusiasm has sparked my own in this wonderful work. This work would never have been completed without his advice and guidance.

I would also like to thank Prof. Kajiware, Prof. Kobayashi and Prof. Nakamura who give me many excellent advices for my research.

I would also like to express my gratitude to Dr. Werawan Manakul, the coordinator of English Engineering Education Program, who supports my life and research in Sapporo.

I would also like to express my gratitude to my parents, who provided me with unconditional advice, support and love. They have never been far from my heart.

APPENDIX A

a. Binary Control Code with Matlab

```
hold on

display('begin');

m=zeros(1,15);

n=0;

PP2=0;

PP3=0;

s = serial('COM5', 'BaudRate', 115200);

fopen(s);

pause(1);

    % send data to arduino

    fwrite(s,strcat(int2str(0),',',int2str(0),',',int2str(0)), 'sync');

for i=1:2500

n=i

    temp=fscanf(s); % get data from arduino

    tempnum=str2num(temp);

    m(i,1:length(tempnum))=tempnum;

    % Displacement calculation

    dis=5*m(:,5)/1023;

    % Force calculation

    f=5*m(:,15)/1023;

    % Time calculation
```

```

    t=m(i,4)/1000;

    if t<5;

        PP2(i)=0;

        PP3(i)=0;

        fwrite(s,strcat(int2str(0),',',int2str(PP2(i)),',',int2str(PP3(i))), 'sync');

        elseif t>5&t2<8

        PP3(i)=0;

        PP2(i)= 255;

        fwrite(s,strcat(int2str(0),',',int2str(PP2(i)),',',int2str(PP3(i))), 'sync');

    else

        PP2(i)=0;

        PP3(i)=0;

        fwrite(s,strcat(int2str(0),',',int2str(PP2(i)),',',int2str(PP3(i))), 'sync');

    end

    end

    display('done');

fclose(s);

delete(s);

```

b. PID Controller Code with Resistance as Feedback

```

kp=4000;

ki=0.2;

kd=0;

input2(i)= sF2(i);

setpoint2(i)=1.47;    %resistance feedback

tlast1=0;

tchange=(now-tlast1);

error1(i)=setpoint1(i)-input1(i);

output1(i)=

output1+kp*(error1(i)-e1)+ki*error1(i)*tchange+kd*(error1(i)-2*e1+e2)/tchange;

if output2(i)>0

    PP2(i)= 0;

elseif output2(i)<-255

    PP2(i)=-255;

else

    PP2(i)=-round(output2(i));

end

PP2(i)=- PP2(i);    % PP2, 0-255, send to arduino to heat the SMA wire

tlast1=now;

e2=e1;

e1=error1(i);

output1= output1(i);

fwrite(s,strcat(int2str(0),',',int2str(PP2(i)),',',int2str(0)),'sync');
```

c. Microcontroller Code

Three PWM outputs and fifteen inputs are designed in this code which can be used to test three segments of SMA wires. In the experiment, only two outputs are used.

```
String comdata = "";

int numdata[3] = {0}, PWMPin[3] = {3, 4, 5}, mark = 0;

int val;

int val1;

unsigned long time;

unsigned int x[3] = {0};

unsigned int y[3] = {0};

unsigned int z[3] = {0};

int analogin[9] = {A0,A1,A2,A3,A4,A5,A6,A7,A8};

void setup()

{

    Serial.begin(115200);

    for(int i = 0; i < 3; i++) pinMode(PWMPin[i], OUTPUT);

}

void loop()

{

    int j = 0;

    while (Serial.available() > 0)                                // check to see if there is
data in the bus

    {
```

```
comdata+=char(Serial.read());

delay(2);

val=analogRead(A11);

val1=analogRead(A15);

mark=1;

}

if(mark==1)

{

    if(comdata.length() > 0)

    {

        for(int i = 0; i < comdata.length() ; i++)

        {

            if(comdata[i] == ',')

            {

                j++;

            }

            else

            {

                numdata[j] = numdata[j] * 10 + (comdata[i] - '0');

            }

        }

    }

    for(int i = 0; i < 3; i++)

        digitalWrite(PWMPin[i],HIGH);
```

```
    for(int j=0;j<3;j++)
    {
        x[i]+=analogRead(analogin[i]);
        y[i]+=analogRead(analogin[i+3]);
        z[i]+=analogRead(analogin[i+6]);
    }

    digitalWrite(PWMPin[i],LOW);

    x[i]=(x[i]/3);
    y[i]=(y[i]/3);
    z[i]=(z[i]/3);

    analogWrite(PWMPin[i],numdata[i]);

    numdata[i] = 0;
}

Serial.print(x[0]);
Serial.print(",");
Serial.print(y[0]);
Serial.print(",");
Serial.print(z[0]);
Serial.print(",");
Serial.print(millis());
Serial.print(",");
Serial.print(val1);
Serial.print(",");
Serial.print(x[1]);
```

```
Serial.print(",");  
  
Serial.print(y[1]);  
  
Serial.print(",");  
  
Serial.print(z[1]);  
  
Serial.print(",");  
  
Serial.print(x[2]);  
  
Serial.print(",");  
  
Serial.print(y[2]);  
  
Serial.print(",");  
  
Serial.print(z[2]);  
  
Serial.print(",");  
  
Serial.print(comdata);  
  
Serial.print(",");  
  
Serial.println(val);  
  
mark = 0;  
  
comdata = String("");  
  
delay(10);  
  
}  
  
}  
  
}
```


APPENDIX B

a. Microcontroller

In the control system, a microcontroller (Arduino Mega 2562, shown in Fig. B-1) is used to collect the data from displacement sensor. The Arduino Mega 2560 is a microcontroller board based on the ATmega2560 (datasheet). It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila. Detailed information is listed in Table B-1.

Arduino Mega 2560



Fig. B-1 Microcontroller used in experiment

Table B-1 Detailed information for microcontroller

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by boot loader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

b. Power Source, Displacement and Force Sensor

Since the SMA wire is heated by current, power source is supplied by TEXIO Kenwood PA18-5B shown in Fig. B-2. The PA-B series is a high-performance DC constant-voltage, constant-current power supply unit with 3.5 digit voltage indicator LEDs and 3-digit current indicator LEDs. The series regulator control allows the user to vary the output from 0 to the rated output. The output controller, a 10-turn winding type variable resistor, offers fine control of output voltage and current. It is possible to set the output voltage and current even the output is off. The output voltage and current may be checked simultaneously. The PA-B series feature output On/Off control, output sensing,

and various remote control functions and fully meet various user needs. They have a wide variety of applications including research and development, prototyping, test, aging, and systems integration. The following is the features of TEXIO Kenwood PA18-5B.



Fig. B-2 Power source used in experiment

Features for TEXIO Kenwood PA18-5B:

- a. Low ripple, low noise
- b. Digital display of voltage & current
- c. Series/parallel operation
- d. Floating output/voltage remote sensing terminal
- e. External analog control for fine adjustments
- f. EIA rack size

In order to detect the output displacement and force of SMA actuator, the displacement and force are obtained by a KEYENCE LC-2000 laser displacement meter (Fig. B-3) and a TEDEA-HUNTLEIGH load cell (Fig. 4), respectively. Since the output displacement of SMA wire is less than 3 mm, the microcontroller can detect the output voltage from displacement sensor directly when setting the displacement output voltage from 0 to 3 V. However, the output voltage of load cell can be regulated shown in Fig. B-4.



Fig. B-3 Displacement sensor used in experiment

Features for KEYENCE LC-2000:

- a. Reference distance :40mm
- b. Measurement range : ± 3 mm
- c. Analog output voltage : ± 3 V
- d. Resolution:0.5 μ m
- e. Accuracy: $\pm 10\mu\text{m}$ $\pm 3\%$



Fig. B-4 Force sensor used in experiment

Features for TEDEA-HUNTLEIGH:

- a. Capacity range: 5kg
- b. Only 22mm high
- c. Aluminum construction
- d. Single point 350 x 350mm
- e. IP66 protection
- f. OIML R60 and NTEP approved

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