Lag-Lead Compensator for Shape Memory Alloy in Gripping Manipulation

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Abstrak

Shape Memory Alloy (SMA) adalah salah satu jenis aktuator yang sedang banyak dipelajari pada aplikasi skala mikro dan nano. Namun di sisi lain, pengembangan pengendalian dalam skala ini masih perlu pengembangan dan penelitian lebih lanjut. Artikel ini mempresentasikan hasil evaluasi tanggapan pergerakan kendali kalang tertutup dari TiNi SMA dalam bentuk spring yang dikendalikan kompensator lag, lead dan lag-lead. SMA yang digunakan berdiameter 50 mm dan berat 350 gram. Sinyal penggerak SMA ini menggunakan modulasi lebar pusla (PWM) sinyal dengan beberapa frekuensi dan duty-cycle. Frekuensi sinyal PWM yang digunakan yaitu 12, 25, 125, 250 and 1150 Hz. Sebagai pengendali, antar muka dan pengambilan data keseleruhan sistem digunakan Lab-View dan DAQ-Card. Gripper yang digunakan terdiri dari dua buah jari dan dapat digerakkan sampai dengan 30^0. Hasil eksperimen dengan kalang tertutup akan ditampilkan dan didiskusikan pada artikel ini. Untuk aplikasi lebih lanjut, maka kendali kalang tertutup juga diuji coba menggunakan kompensator lag, lead dan lag-lead. Dengan menggunakan kendali kalang tertutup ini, maka waktu untuk mencapai rise-time menjadi lebih singkat dan tingkat galat kondisi tunak menjadi lebih kecil.

Kata kunci: Gripper, Lag-Lead Compensator, PWM, Shape Memory Alloy (SMA).

Abstract

Shape Memory Alloy (SMA) is emerging actuator for micro and nano application which is interesting to be developed. This paper presents the evaluation of close-loop controller responses of the TiNi SMA spring based gripper by introducing lag, lead and lag-lead compensator. A SMA spring has a diameter of 50 mm wire and 350 gram hanging mass. The driver of the SMA actuator uses pulse width modulation (PWM) signal and it is tested by varying frequencies and duty-cycles. The applied frequencies in this study are 12, 25, 125, 250 and 1150 Hz. Lab-View and DAQ-Card is used as a controller, interfacer and data recorder of the system. The fabricated gripper consists of two fingers and the total angular displacement of the gripper is 30^0. In advanced application, the experiment coversSMA open loop and close-loop system. The SMA response indicated that the rise-time and the steady-state error of the clooploop are shorter and lower than open-loop controller.

Keywords: Gripper, Lag-Lead Compensator, PWM, Shape Memory Alloy (SMA).

1. Introduction

Shape memory alloy (SMA) is emerging actuator for MEMS (Microelectromechanical system) and NEMS (Nanoelectromechanical system) applications and it has been widely used as prospective candidate for micro and nano actuation [1]. The SMA responds the temperature by changing their shape and generates force and displacement [2], [3]. The responses of the SMA can be generated by using electro-thermal energy. The SMA is inter-metallic alloys, so they can be driven by electrical current via Joule heating which is easy and efficient way [2], [3].

The shape memory alloy usually consists of single piece of metal, and spring is one of their forms [4]. The SMA spring has been used on many applications extensively in medicine and robotics. According to [1], the SMA spring can be directly actuated by electrical current. They investigated the characteristics of the SMA spring by the alternating and direct current

electro-thermal driving. As the results in [1] state that "the most important two-way shape memory effect characteristic is its magnitude and response time".

The electrical actuation of the MEMS has been widely considerate by many researchers. The electrical actuation on many applications of MEMS is voltage based controller [5], current based controller [1] and frequency based controller [4].

SMA actuators has a good high power/ weight ratio, produce a large displacement in a limited space, it has good transformation temperatures and an excellent mechanical properties such as ductility and toughness [5]. Gripping principles include vacuum suction, shape memory effect, piezo actuation, magnetic actuation, electrothermal effect and also laser trapping.

The gripper mechanism which the actuation is provided by SMA and driven by an electrical has published in [6]. The other grippers have also been published and developed by researcher for any purposes, such as the electrostatic microgripper [7], development of the endoscopic tip actuator [8], the microgripper for holding the chip [9], and also the electric piston for the gripper finger [4].
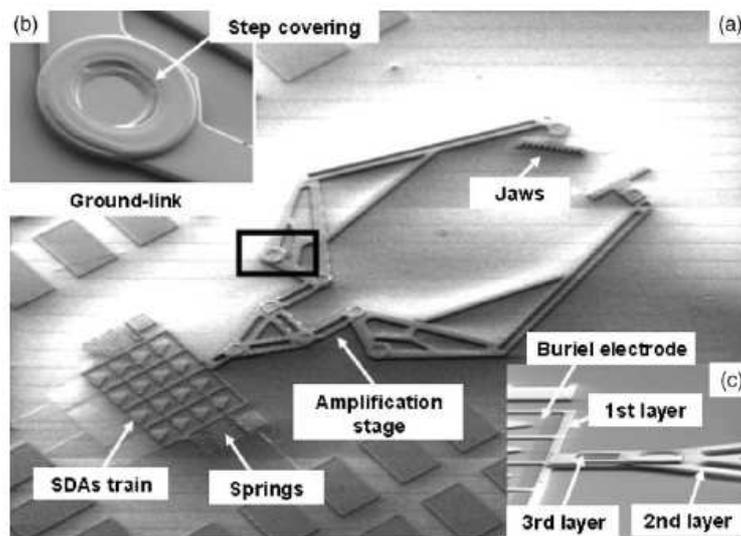

Figure 1. Electrostatic microgripper, combination of a linear motor, an amplification mechanism and a grasping stage [7]
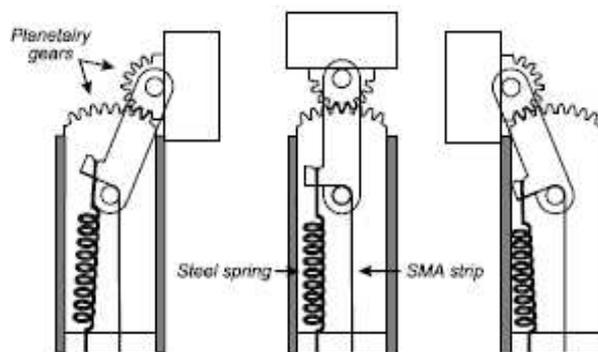

Figure 2. The endoscopic tip actuator [8]

Although the application of SMA as an actuator has been considered in a lot of field, the induction of advanced control in such applications must be improved. This paper is to evaluate the lag, lead and lag-lead compensator which as the one type of algorithm control as possible controller of SMA actuator.

2. Methods and Set-Up
2.1 Gripper Design
The movement of the gripper in this study is actuated by a SMA spring. The gripper mechanism (in mm) is shown in Figure 3. The material of the gripper is with a thickness of 2 mm Aluminium (Al). The hole of A and B are used as a center of movement of the gripper. This hole is also used to assemble the position sensor. The bottom holes are used for the spring hook.
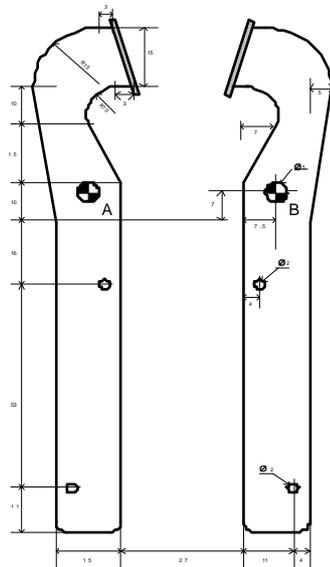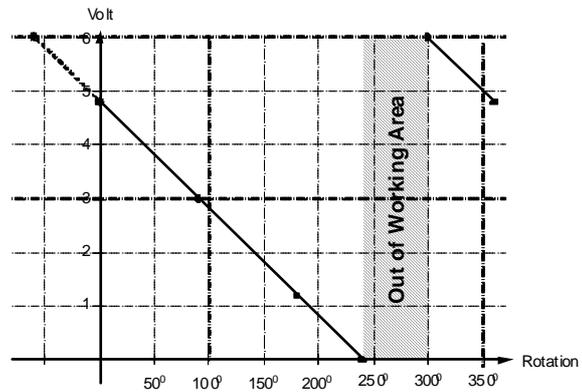

Figure 3. Gripper consisting of two fingers

Figure 4. Voltage to degree chart converter of potentiometer.

2.2 Position Sensor
The position sensor used was a rotary potentiometer with a 5KΩ of resistance. This potentiometer has shaft diameter of 5.5 mm, shaft length of 10 mm and linear resistance (type B). The total rotation of this potentiometer is 3000. In this study, the gripper movements are measured by the position sensor by employing a 5 KΩ of potentiometer. At the default position of gripper, the output voltage of the potentiometer is 3 volt and at the maximum retraction position of the spring is 2.7 volt. The total angular rotation of the gripper (θ) is $15^0+15^0=30^0$. The voltage of power supply is given 6 volt. The converter chart (voltage to degree) is illustrated in Figure 4.
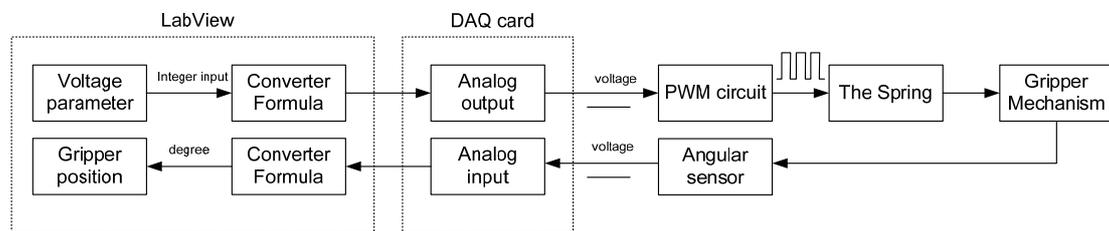

Figure 5. Block diagram of the system

2.3 Programming
The computer software used is LabView, which is a trademark of National Instruments Corporation. LabView is used to display the movement responses of the gripper and also to

send the voltage input of the pulse width modulation (PWM) circuit. Another trademark of National Instrument Corporation used in this study is DAQ card PCI NI-6024E.

The relationship between LabView, DAQ card, PWM circuit, the spring and the position sensor is illustrated in Figure 5 and the front panel of Lab View presented in Figure 6.
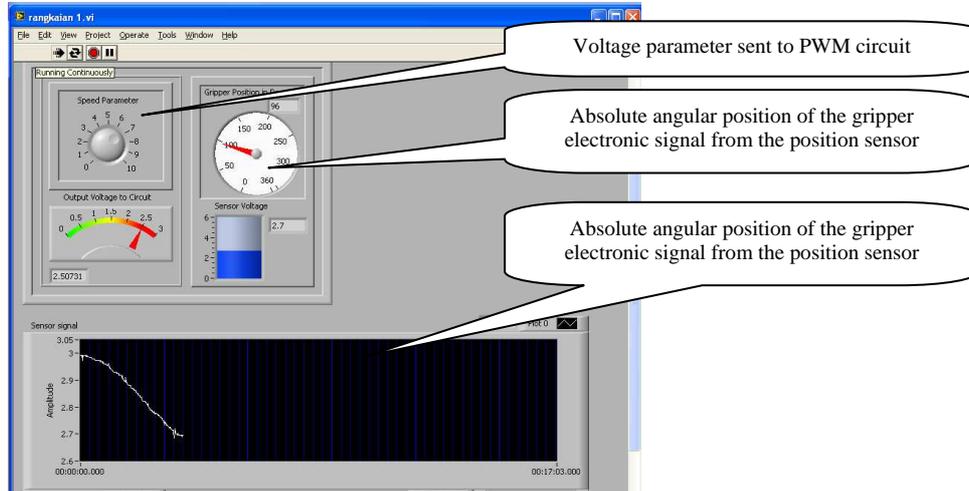
Figure 6. LabView front panel of gripper angular measurement.

3. Results and Discussions
3.1 SMA Spring Responses to PWM Signal

The first performance test is to analyse the movement responses of SMA Spring actuated by varying frequencies and duty cycles of PWM signal. The frequency of PWM signal used is 12, 25, 125, 250 and 1150 Hz and duty cycles varying from 20% to 90%. The movement response of SMA spring to achieve the position destination (time versus displacement) is recorded by Lab View and presented in Figure 7. According to Figure 7 the fastest response of the SMA spring is actuated by 125 Hz PWM signal.
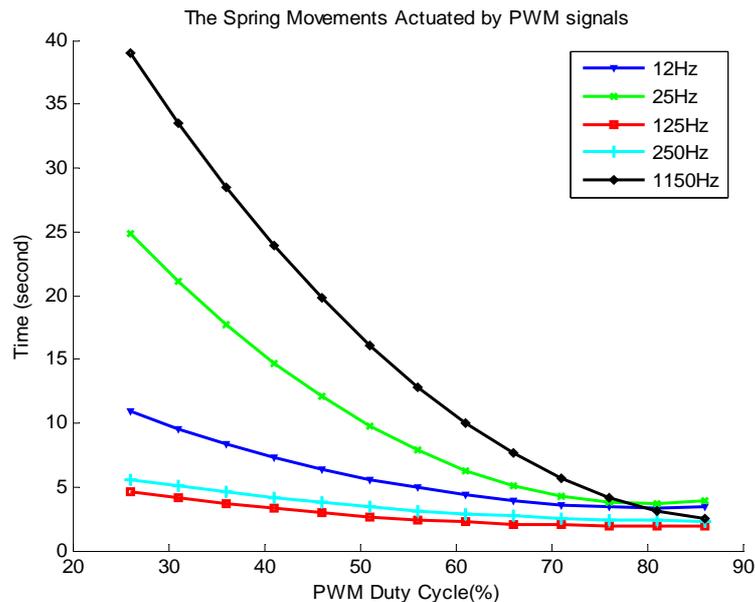
Figure 7. Spring movements actuated by several frequencies of PWM signals.

3.2 Lead and Lag Compensator

In this study, a number of tests on position control of the gripper are conducted by using lag, lead and lag-lead compensators. The signal in previous experimentations is employed in this experiment. The signal employed is 125Hz of PWM signal due to this signal had a faster movement response.

The transfer function of the lead compensator is [10]:

$$Gc(s) = Kc\frac{s + 1/T}{s + 1/\alpha T} \tag{1}$$

where α and T are determined from the angle deficiency. Kc is determined from the requirement of the open-loop gain and $1/T$ is less than $1/\alpha T$.

To simplify the calculation, it can be assumed that:

$$1/T = a \tag{2}$$

$$1/\alpha T = b \tag{3}$$

By inserting equation (2) and equation (3) into equation (1), it can be derived that:

$$Gc(s) = Kc\frac{s + a}{s + b} \tag{4}$$

By using Tustin's method (bilinear approximation) [10], the equation (4) can be converted into Z domain. The Tustin's method is given:

$$s = \frac{2}{T}\frac{(z - 1)}{(z + 1)} \tag{5}$$

By inserting Eq. 5 into Eq. 4, it can be derived:

$$\frac{U(z)}{E(z)} = Kc\frac{2(z - 1) + aT(z + 1)}{2(z - 1) + bT(z + 1)} \tag{6}$$

By some mathematical manipulation, equation (6) becomes

$$E(z)(2Kc+aTKc)+z-1E(z)(-2Kc+aTKc)+U(z)z-1(2-bT)=U(z)(2+bT) \tag{7}$$

$$e(k)(2Kc+aTKc)+e(k-1)(-2Kc+aTKc)+u(k-1)(2-bT)=u(k)(2+bT) \tag{8}$$

The output of the lead compensator is:

$$u(k) = \frac{e(k)(2Kc + aTKc) + e(k - 1)(-2Kc + aTKc) + u(k - 1)(2 - bT)}{(2 + bT)} \tag{9}$$

The difference of lag and lead compensator [10] is:

$$Gc(s) = Kc\frac{s + a}{s + b}$$　　　　if a > b ➔ lag compensator,

　　　　　　　　　　　　if a < b ➔ lead compensator

To obtain the control performance of the gripper system, the optimal gains of the lag and the lead compensator were determined by experimentally tuning of the gains. A number of tests on the gripper system response were conducted. The gains were also limited by DAQ card

specification and PWM input requirements. The block diagram and the LabView program of the lag and the lead compensator are presented in Figure 8 and Figure 9, respectively.
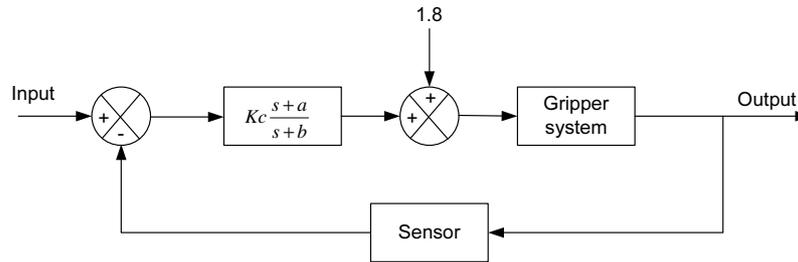

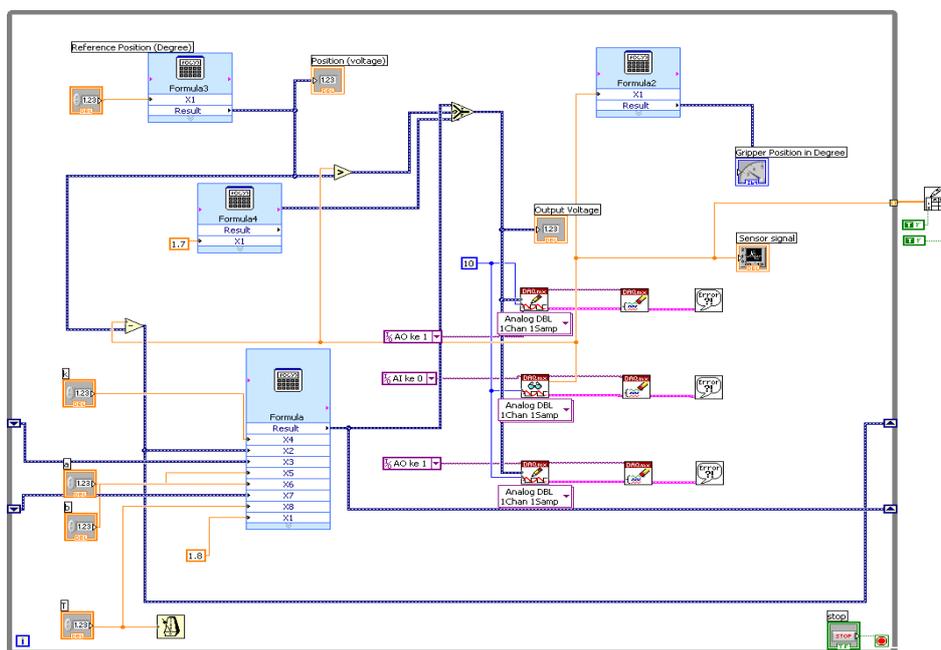Figure 8. Block diagram of the lead and the lag compensator.

Figure 9 LabView program of the lag and the lead compensator.

The responses of the closed-loop control with the lead compensator by using different gains are shown in Figure 10 and the lag response is presented in Figure 11. The rise time and the steady state error of the lag compensator and the lead compensator are presented in Table 1.
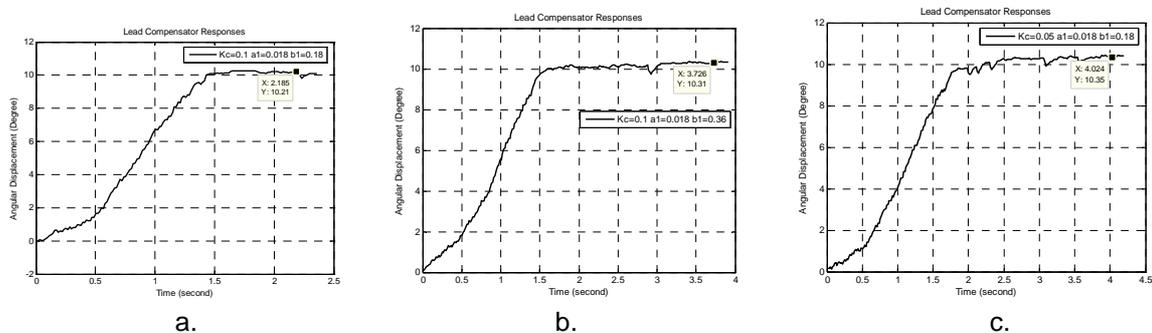

Figure 10. The lead compensator response with (a). Kc=0.1, a=0.018 and b=0.18, (b). Kc=0.1, a=0.018 and b=0.36, (c). Kc=0.05, a=0.018 and b=0.18
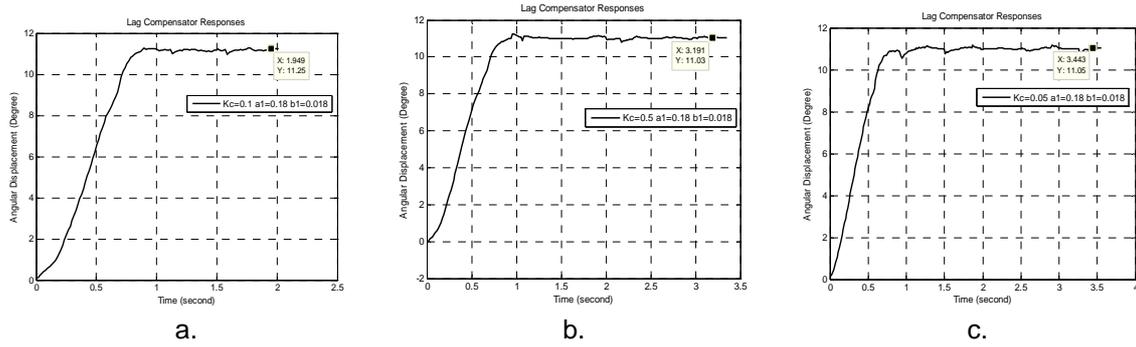
Figure 11. The lag compensator response with (a). Kc=0.1, a=0.18 and b=0.018, (b). Kc=0.5, a=0.18 and b=0.018, (c). Kc=0.05, a=0.18 and b=0.018.

Table 1. The response of the closed-loop control with the lead and the lag compensator

No	Lead compensator					Lag compensator				
	Kc	a	b	Rise Time (second)	Steady State Error (%)	Kc	a	b	Rise Time (second)	Steady State Error (%)
1	0.1	0.018	0.18	0.9434	2.10	0.1	0.18	0.018	0.6602	12.50
2	0.1	0.018	0.36	1.1318	3.10	0.5	0.18	0.018	0.6445	10.30
3	0.05	0.018	0.18	1.2893	3.50	0.05	0.18	0.018	0.5659	10.50
4	0.5	0.018	0.18	1.5253	3.70	0.1	0.18	0.09	1.981	1.10

3.3 Lag-Lead Compensator

The transfer function of the lag-lead compensator is [9]:

$$Gc(s) = Kc\left(\frac{s + \frac{1}{T1}}{s + \frac{\gamma}{T1}}\right)\left(\frac{s + \frac{1}{T2}}{s + \frac{1}{\beta T2}}\right) \tag{10}$$

To simplify the calculation, it can be assumed that:

$$\frac{1}{T} = a_1 , \; \frac{\gamma}{T1} = b_1 \tag{11}$$

$$\frac{1}{T2} = a_2 , \; \frac{1}{\beta T2} = b_2 \tag{12}$$

By inserting equation (11) and equation (12) into equation (10), it can be derived that:

$$Gc(s) = Kc\left(\frac{s + a_1}{s + b_1}\right)\left(\frac{s + a_2}{s + b_2}\right) \tag{13}$$

By using same procedures with lead compensator, the output of the lag-lead compensator is:

$$u(k) = \frac{A + B}{(4 + 2b_2 T + 2b_1 T + b_1 b_2 T^2)} \tag{14}$$

where A=A$_1$+A$_2$

$$A_1 = e(k - 2)(4Kc - 2a_2 TKc - 2a_1 TKc + a_1 a_2 T^2 Kc) + e(k - 1)(-8Kc + 2a_1 a_2 T^2 Kc) \tag{15}$$

$$A_2 = e(k)(4Kc + 2a_2TKc + 2a_1TKc + a_1a_2T^2Kc) \tag{16}$$

$$B = -u(k-2)(4 - 2b_2T - 2b_1T + b_1b_2T^2) - u(k-1)(-8 + 2b_1b_2T^2) \tag{17}$$

The block diagram and the LabView program of the lag-lead compensator are presented in Figure 12 and Figure 13, respectively. The responses of the closed-loop control with the lag-lead compensator by using different gains are shown in Figure 14. The rise time and the steady state error of the lag-lead compensator are presented in Table 2.
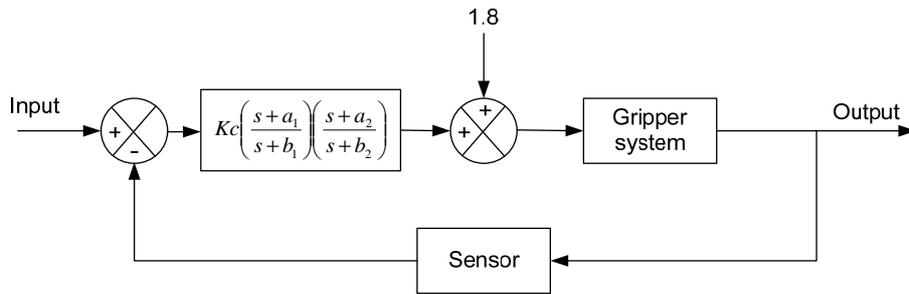
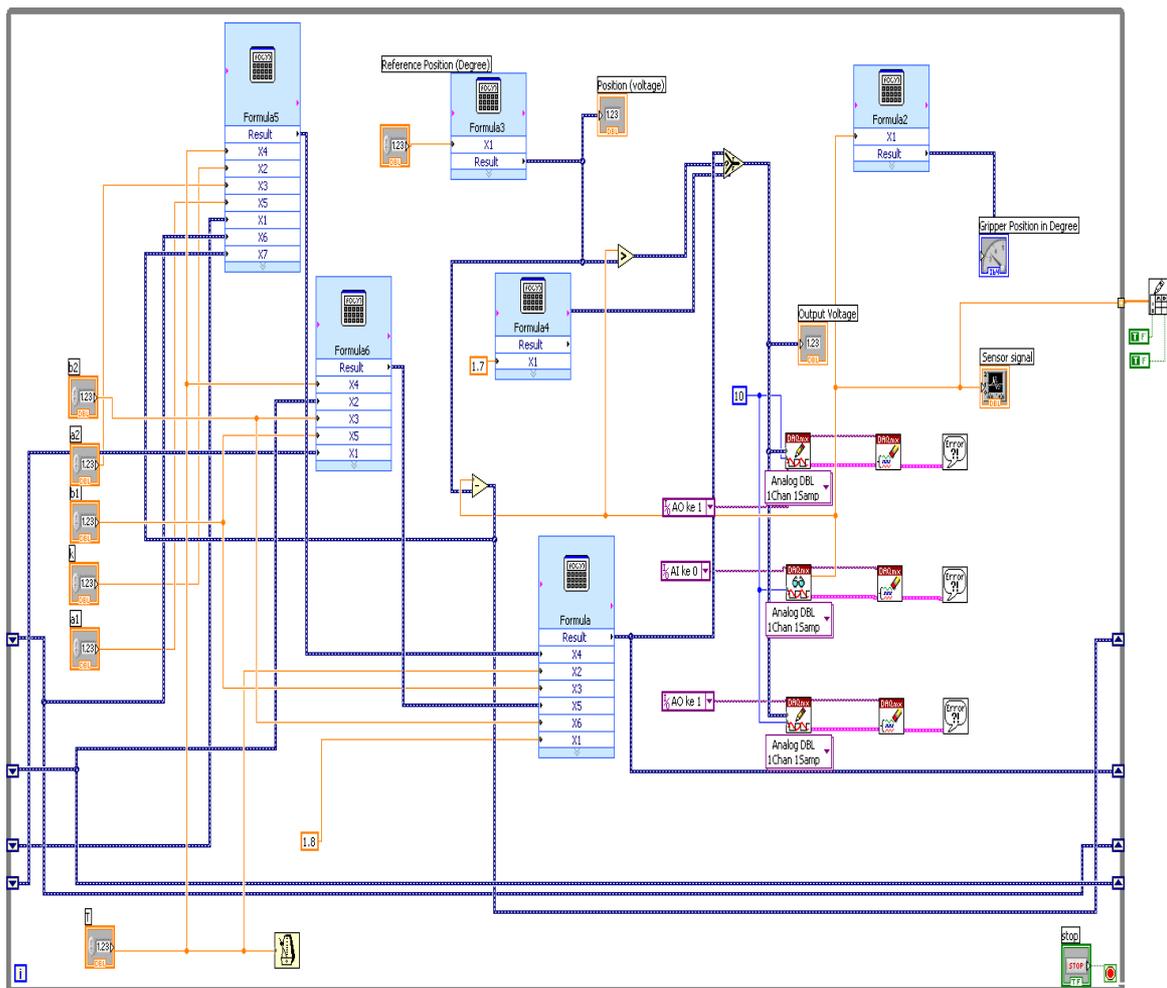Figure 12. The block diagram of the lag-lead compensator.

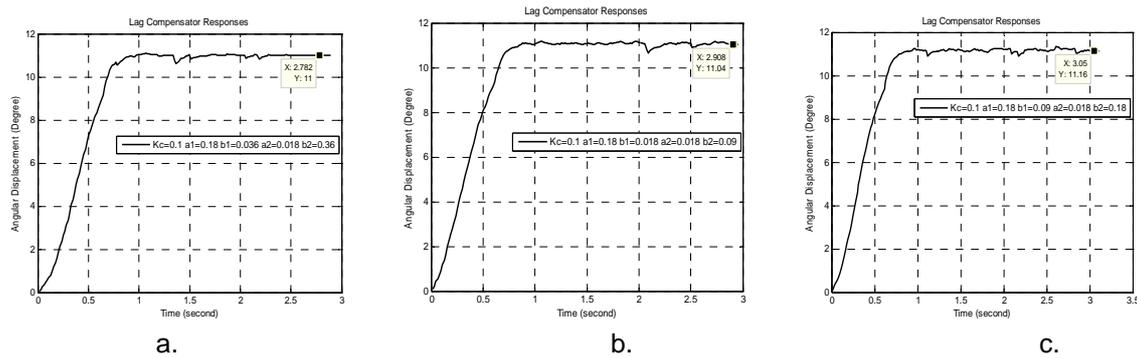Figure 13. The LabView program of the lag-lead compensator.

Figure 14. The lag-lead compensator response with (a). b1=0.036, a2=0.018 and b2=0.36, (b). b1=0.018, a2=0.018 and b2=0.09, (c). b1=0.09, a2=0.018 and b2=0.18.

Table 2. The response of the closed-loop control with the lag-lead compensator

No	Kc	a_1	b_1	a_2	b_2	Rise Time (second)	Steady State Error (%)
1	0.1	0.18	0.036	0.018	0.36	0.6445	10.00
2	0.1	0.18	0.018	0.018	0.09	0.5816	10.40
3	0.1	0.18	0.09	0.018	0.18	0.5659	11.60
4	0.1	0.18	0.09	0.018	0.09	0.6917	12.10

4. Conclusions

A number of tests on the performance characterization of the SMA spring were conducted. The performance characterization experiment of the SMA spring is the movement response. The movement response experiment is conducted with applying different frequencies and different duty cycles of PWM signals. The 125 Hz frequencies are likely to have the fastest response of the SMA spring.

In this study, a number of tests on position control of the gripper are also conducted by using lag, lead and lag-lead compensators. The tuning of the gain is based on experimentally tuning. The experiment results indicated that the rise time of the gripper system was shorter (approximately 10 times) than the open-loop controller. On the other hand the smallest steady state error is obtained by lead compensator. The lag, lead and lag-lead compensator are likely to be reliable and suitable controllers for close loop controller of the SMA spring for the future.

One of the SMA characteristic is that the SMA has a fast response when heated but slower on cooling. The SMA has disadvantage at cooling problems. By developing the cooling system of the SMA, the performance of the gripper will be significantly improved.

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