

**DESIGN, FABRICATION AND CONTROL OF A NOVEL  
SHAPE MEMORY ALLOY (SMA)-WIRE-BASED FLEXIBLE  
COMPOSITE ACTUATOR**

**ÖZGÜN BİR ŞEKİL BELLEK ALAŞIM (ŞBA) TABANLI  
ESNEK KOMPOZİT EYLEYİCİNİN TASARIMI, ÜRETİMİ  
VE DENETİMİ**

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## **ABSTRACT**

# **DESIGN, FABRICATION AND CONTROL OF A NOVEL SHAPE MEMORY ALLOY (SMA)-WIRE-BASED FLEXIBLE COMPOSITE ACTUATOR**

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Soft actuators are frequently seen in many design areas. They can adapt to the desired motion and do not harm the material they touch. These features give many ideas to designers. In this thesis, such a soft composite actuator, a spiral, has been designed. It is a novel design with its geometry, functionality and actuation stroke; providing automatic movement in its gripper-type implementation.

In the process leading to the design, first of all, the phenomena about material behavior of the shape memory alloy (SMA), which is the main component and provides the actuation, are discussed. In this study, the SMA wire is used as an actuator. SMA materials exhibit thermomechanical properties. In other words, the mechanical actuation is provided by the heating of the wire. The phase transitions of the SMA material follow different curves during heating (from the martensite phase to the austenite phase) and cooling (from the austenite phase to the martensite phase) due to hysteresis behaviour. Therefore, the model is separately constructed for both states. Transition start and finish temperatures are needed

to model the phase changes. Another feature of SMA materials is that the phase transition temperatures also change according to the load hanging from the wire. Therefore, in the study, the characterization of the wire is carried out.

A thermal model is the first for the constitutive equations modeling the thermomechanical property of SMAs. In this study, it is shown that the specific heat coefficient, latent heat coefficient and convection coefficient of the heat conduction model can be estimated by the recursive least squares (RLS) method. It is particularly important that convection coefficient is predictable and considers relatively complex mathematics in its determination, since the convection coefficient varies with the environment. Additionally, the specific heat and the latent heat coefficient are not always available from the material supplier. In the study, the functionality of the method is shown for two different wires. It is also understood that by adding the latent heat term to the heat transfer equation, there can be a 28% improvement of the model for one wire and a 35% improvement in the model for the other.

The control of SMA wire under axial loading is studied. Reference tracking is provided with the PI controller. The performance of the controller is separately tested for the regions where phase transition exists or does not exist and with regard to increasing reference frequency. In addition, it is shown that the controller exhibits a robust performance under varying load.

In this study, the material used while creating the soft composite structure is thermoplastic polyurethane (TPU). The main structure, the spiral's geometry is obtained with a 3D printer. If compared to harder equivalent composite production methods such as curing and molding, this method makes the production much easier.

The spiral exhibits an elastic effect because of its circumvolute structure. With the adding of the flexibility of the TPU, the composite can be achieved to return to its initial position after the actuation. In other words, a two-way actuator is obtained by means of the novel geometry.

The spiral has curvilinear motion. Moreover, it can be predicted that the composite structure will produce a highly non-linear response when TPU flexibility and SMA hysteresis are

combined. However, the control of the free end of the spiral is provided by PID controller. The feedback here is displacement data taken from the one direction in the plane.

A load-bearing gripper is presented as an implementation in which two spirals are used. In similar designs, the actuator system that grasps the load is moved upwards by the user. After the grip, a 6.5gr load can be automatically lifted up by 6.5mm with the double spiral application.

Accordingly, the heat transfer equation for the spiral takes the natural convection as the only energy loss. The equation gives results that match the measured temperatures, thanks to the parameters estimated by RLS. Therefore, firstly, it is inferred from the comparison of the model results with the measurements that the model is suitable for the spiral. Secondly, it is shown that the RLS method is effective when estimated parameters are taken into account.

**Keywords:** Shape Memory Alloy Wire, Parameter Estimation, Recursive Least Square Method, Soft Composite Actuator, Spiral Actuator, Actuator Control

## ÖZET

### ÖZGÜN BİR ŞEKİL BELLEK ALAŞIM (ŞBA) TABANLI ESNEK KOMPOZİT EYLEYİCİNİN TASARIMI, ÜRETİMİ VE DENETİMİ

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Yumuşak eyleyicilerle pek çok alanda, sıklıkla karşılaşılmaktadır. İstenen harekete uyum sağlayabilen, değdiği materyale zarar vermeyen özellikleri tasarımcılara birçok fikir vermektedir. Bu tezde, bu nevi yumuşak kompozit bir eyleyici, spiral, ortaya çıkarılmıştır. Tasarım, geometrisi, işlevselliği, tahrik mesafesi ve kısaç tipi eyleyici tasarımında otomatik hareket sağlaması ile özgündür.

Tasarıma giden süreçte, öncelikle, tasarımın temel bileşeni olan, tahriki sağlayan şekil bellek alaşımın (ŞBA) bir malzeme olarak davranışına dair olgular ele alınmaktadır. Bu çalışmada, eyleyici olarak ŞBA tel kullanılmaktadır. ŞBA malzemeler termomekanik özellik göstermektedir. Yani, mekanik tahrik, telin ısınması ile sağlanmaktadır. ŞBA malzemenin faz geçişi ısınırken ve soğurken farklı eğriler takip etmektedir; yani, davranış histeriktir. Bu nedenle, model her iki durum için ayrı ayrı oluşturulmaktadır. Martensitten östenite, östenitten martensite faz değişimlerini modellemek için değişimlerin başladığı sıcaklıklara ihtiyaç duyulmaktadır. ŞBA malzemelerin bir diğer özelliği ise faz

değişim sıcaklıklarının tele asılan yüke göre de değişmesidir. Dolayısıyla, çalışmada, telin karakterizasyonu yapılmaktadır.

Termomekanik özelliğini modelleyen bünye denklemlerinin de ilk basamağı termal modeldir. Bu çalışmada ısı iletim modelinin öz ısısının, faz değiştirme sabitinin ve ısı yayım sabitinin yinelemeli en küçük kareler (YEK) yöntemi ile kestirilebileceği gösterilmektedir. Isı yayım sabiti, ortama göre değiştiği için belirlenmesindeki nipten karmaşık matematik yerine, kestirilebilir oluşu özellikle önemlidir. Yine, öz ısı ve faz değiştirme sabiti de malzeme sağlayıcıdan her zaman ulaşılabilen sabitler değildir. Çalışmada, iki farklı tel için yöntemin işlevselliği gösterilmektedir. Ayrıca, ısı iletimi denkliğine, faz değiştirme ısısı teriminin eklenmesi ile bir telde %28, diğerinde %35 kadar model iyileşmesi olabildiği de anlaşılmaktadır.

ŞBA telin axial yükleme altında denetimi üzerinde çalışılmıştır. PI denetleyici ile referans takibi sağlanmaktadır. Artan referans frekansı ve faz değişimi olan/olmayan bölgelerde denetleticinin başarımı ayrı ayrı sınanmıştır. Ayrıca, denetleyicinin, değişen yük altında da gürbüz bir başarımlı sergilediği görülmektedir.

Bu çalışmada, yumuşak kompozit yapı oluşturulurken kullanılan malzeme termoplastik poliüretandır (TPU). Spiral geometri 3B yazıcı ile elde edilmektedir. Kütleme, kalıplama gibi külfetli, muadil kompozit üretim yöntemlerine göre, bu teknik, üretimi hayli kolaylaştırılmaktadır.

Spiralin içe katlı yapısı elastik bir özellik sağlamaktadır. Yumuşak ana yapıda kullanılan TPU esnekliğiyle de birlikte, tahrikinin ardından kompozit yapı başlangıç konumuna geri dönebilmektedir. Başka bir deyişle, bu özgün geometri sayesinde çift yönlü bir eyleyici elde edilebilmektedir.

Spiral, düzlemde eğrisel hareket etmektedir. Ayrıca, TPU esnekliği ile ŞBA histerisi birleştiğinde, kompozit yapının fazlasıyla doğrusal olmayan bir tepki üreteceği ön görülebilmektedir. Buna rağmen, düzlemde, tek eksen yönünde alınan mesafe verisi geri beslemesi olmak üzere, spiralın serbest ucunun kontrolü PID ile sağlanmaktadır.

İki adet spiral kullanılarak, yük taşıyıcı kısaç uygulaması önerilmektedir. Benzer tasarımlarda, tutunma sonrası, yükü kavrayan eyleyici sistemi kullanıcı tarafından yukarı doğru hareket ettirilmekteyken, çift spiral ile 6.5gr'lık bir yük otomatik olarak 6.5mm kadar yükseltilebilmektedir.

Son olarak, YEK yöntemi spiral için de uygulanmaktadır. Buna göre, spiral için ısı iletimi denkliği, doğal ısı yayımını tek kayıp olarak almaktadır. Denklik, YEK ile kestirilen parametreler sayesinde, ölçülen sıcaklıklarla örtüşen sonuçlar vermektedir. Dolayısıyla, hem kestirilen parametrelerle YEK'nin etkinliği, hem de, model ile ölçüm karşılaştırılarak, ısı iletim modelinin spiral için uygunluğu gösterilmektedir.

**Keywords:** Akıllı Bellek Alaşımli Tel, Parametre Tahmini, Yinelemeli En Küçük Kareler Yöntemi, Yumuşak Kompozit Eyleyici, Spiral Eyleyici, Eyleyici Kontrolü

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## ABBREVIATIONS AND LIST OF SYMBOLS

|            |                                              |
|------------|----------------------------------------------|
| <b>DSC</b> | : Differential Scanning Calorimetry          |
| <b>PCB</b> | : Printed Circuit Board                      |
| <b>PWM</b> | : Pulse Width Modulation                     |
| <b>RGB</b> | : Red Green Blue Color Codes                 |
| <b>RLS</b> | : Recursive Least Square                     |
| <b>SMA</b> | : Shape Memory Alloy                         |
| <b>TPU</b> | : Thermoplastic Polyurethane                 |
| $A$        | : SMA wire surface area                      |
| $A_f$      | : Austenite finish temperature               |
| $A_s$      | : Austenite start temperature                |
| $B_{at}$   | : Backward actuation time                    |
| $B_{dt}$   | : Backward delay time                        |
| $B_f$      | : Backward finish time                       |
| $B_s$      | : Backward start time                        |
| $C$        | : SMA wire specific heat coefficient         |
| $D$        | : SMA wire diameter                          |
| $D_{max}$  | : Maximum constant spiral distance           |
| $d_c$      | : Length of the arches                       |
| $d_o$      | : Length of the pockets                      |
| $F_{at}$   | : Forward actuation time                     |
| $F_{ct}$   | : Forward constant time                      |
| $F_f$      | : Forward finish time                        |
| $F_s$      | : Forward SMA start time                     |
| $h$        | : Heat transfer coefficient                  |
| $I$        | : Electrical current                         |
| $I_{off}$  | : The electrical current is cutting off time |

|                   |                                                               |
|-------------------|---------------------------------------------------------------|
| $L$               | : SMA wire length                                             |
| $M_f$             | : Martensite finish temperature                               |
| $M_s$             | : Martensite finish temperature                               |
| $N$               | : Measurement number                                          |
| $R$               | : SMA wire electrical resistance                              |
| $R_i$             | : Following spiral cycle radiuses                             |
| $R_{dt}$          | : Maximum constant distance and total actuation time ratio    |
| $R_{dtB}$         | : Maximum constant distance and backward actuation time ratio |
| $R_{dtF}$         | : Maximum constant distance and forward actuation time ratio  |
| $r$               | : First spiral cycle radius                                   |
| $T$               | : Temperature                                                 |
| $T_{at}$          | : Total actuation time                                        |
| $T_{\infty}$      | : Ambient temperature                                         |
| $t$               | : Time                                                        |
| $V$               | : SMA wire volume                                             |
| $V_s$             | : Video recording start time                                  |
| $V(\hat{\theta})$ | : Cost function                                               |
| $Y$               | : System output vector                                        |
| $y(t)$            | : System output                                               |
| $\alpha_{ic}$     | : Angles of the arches                                        |
| $\alpha_{io}$     | : Angles of the pockets                                       |
| $\Delta h$        | : Latent heat coefficient                                     |
| $\delta$          | : Temperature difference                                      |
| $\dot{\delta}$    | : Rate of temperature difference                              |
| $\epsilon(t)$     | : Estimation error                                            |
| $\varepsilon$     | : Strain                                                      |
| $\theta$          | : Unknown parameters vector                                   |
| $\hat{\theta}$    | : Estimation vector                                           |
| $\lambda$         | : Forgetting factor                                           |

|              |   |                             |
|--------------|---|-----------------------------|
| $\xi$        | : | Martensite fraction         |
| $\dot{\xi}$  | : | Rate of martensite fraction |
| $\rho$       | : | SMA wire density            |
| $\sigma$     | : | Stress                      |
| $\Phi$       | : | Measurement matrix          |
| $\varphi(t)$ | : | Data vector                 |



# **1. INTRODUCTION**

Actuators have been designed by using smart materials since over two decades. One of materials is shape memory alloy (SMA) as well. Also, in recent years, composite structures in which some soft materials as a secondary are used, have been started to be used for actuation. Control action is also another important subject to obtain desired activation in actuation design studies. In this context, in this chapter, main content that this study focused on is given in the title "Scope Of The Thesis", the novel part of the this thesis is presented in the title "Contributions" and the following chapters of the thesis with the main lines are presented in the title "Organization".

## **1.1. Scope Of The Thesis**

This thesis mainly focuses on designing an actuator. The actuator is a kind of soft composite. It is a composite with the material providing actuation and soft with the flexible secondary material. This design has some advantages such as being non-destructive while used and compactness.

The design is cost effective, fast and laborless in terms of its production.

The design provides two-way actuation. It means the design has returning capability to the initial position and conditions when excitation is eliminated and cycling actuation.

A simple model corresponding to the system behaviour can be obtained for the model. The design model has predictability. It means the model parameters can be estimated mathematically.

The actuator design can be controlled. The controller can track the desired reference signal and also, the controller has robust performance.

Lastly, the design is a functional and utilizable actuator in real-world implementations.

## 1.2. Contributions

The main contributions of this study can be summarized as follows:

- Heat transfer model parameters for an SMA have been estimated by using recursive Least Square (RLS) method.
- The model including estimated parameters has been validated with measured temperatures and also, by repeating the procedure for another wire with different diameter.
- It has been shown that the addition of the latent heat energy term to the model provides positive contribution.
- The study above has been published in an SCI journal [1].
- A controller has been designed for SMA wire under load and it has been experimentally shown that the control is robust against changing loads.
- A new example design has been presented to SMA-based soft composite structures. Thermoplastic Polyurethane (TPU) has been used in the composite as a soft secondary material.
- The new design is *spiral*. This design is novel with its geometry and functionality. Accordingly, all of the following items related to the spiral design are contributions.
- The design has been simply produced by 3D printing without going into any complex production methods.
- Performance analyses have been carried out for the spiral designed as actuator. Image processing method has been performed during the studies for which the optimal spiral has been chosen.
- Two-way actuator has been achieved by means of both the novel geometry of the design and the flexibility of TPU.

- The spiral actuator exhibits curvilinear motion. There are non-linearities coming from the flexibility of TPU and hysteresis characteristics of the SMA wire. Nevertheless, the spiral actuator has been successfully controlled with the displacement feedback signal measured from only one planar direction.
- RLS method has been applied for the spiral. It has been shown that the convection model without considering the radiation and the conduction structure is available to describe heat transfer although the design is composite. The temperature outputs of the model including estimated parameters have been validated with measured temperatures.
- A weight-lifting up application has been presented by using two spiral actuators. A weight is externally lifted up after clamping in equivalent gripper-like implementations. But, this has been performed automatically in this study. The height automatically lifted up is appreciable considering the equivalent studies again.

### **1.3. Organization**

The organization of the thesis is as follows:

- Chapter 1 presents the study's motivation, contributions and the scope of the thesis.
- Chapter 2 provides the background information for the comprehension of SMA material properties, its modeling, model parameter estimation, SMA based soft actuators and actuator control.
- Chapter 3 presents models for the SMA wire, the SMA characterization and the model validation.
- Chapter 4 introduces RLS method mathematically. Then, implementation of the method to the heat transfer model of the SMA wire and the results are given. Model validation with estimated parameters is discussed considering measured data and the results of another wire with different diameter.

- Chapter 5 gives the results of the SMA wire control in both complete and restricted operation points for different desired reference signals. The tracking performance of the controller and its robustness under variable stresses are discussed.
- Chapter 6 presents a novel SMA based soft composite actuator design, i.e. the spiral, with all details about its fabrication, selection of the optimal one, constraints of its usage, its control and the application it is used as an actuator.
- Chapter 7 presents the results and validation of the RLS method which is applied for the spiral design in this time.
- Chapter 8 briefs the general discussions about the previous chapters and conclusions of the thesis.
- Chapter 9 gives some final suggestions for the future studies.

## 2. BACKGROUND OVERVIEW

In this section, firstly, general features of SMA materials are mentioned. Then, brief knowledges are presented about SMA modeling and estimation method of the model parameters, its usage as an actuator and its control.

### 2.1. Shape Memory Alloys

Engineers have developed new materials from several metallic materials to utilize their different properties such as mechanical, electrical, magnetic, thermal, etc., by using variable methods for many years. Also, some special ones in these materials are called active [2] or smart [3] or adaptive [4] materials because of their sensing and actuation capabilities. Shape memory alloy is one of materials such as piezoelectrics or magnetostrictives [2]. There are copper based and nickel-titanium based alloys and also these can be alloyed by some different elements such as Al, Zn or NiTiCu compound [3]. However, especially for actuators, Nitinol discovered in Naval Ordnance Laboratory (NOL) is actively and generally used in many studies [2].

SMAs are defined as with memory because they can remember their original shapes before exposure to any type of deformation like torsion, tension or flexion [3]. They have martensite phase at low temperatures and austenite phase at high temperatures. The recovery to the initial shape occurs during the transition between these phases. The deformed shape can be recovered by means of shape memory effect (SME) or thermomechanical property of SMAs. The complete phenomenon can be seen in figure 2.1 and a simple example is given in figure 2.2 to get it clear. According to SME, an SMA material can recover its initial shape if heated to austenite finish temperature (as being in path of D-E-F or until point A) after the weight causing the deformation from twinned array to detwinned array (between start stress  $\sigma_s$  and finish stress  $\sigma_f$ ) in martensite phase (between points B and C) is unloaded (at point C). Then, while no deformation remaining, material can return to twinned martensite state by cooling

(from points A or F to point B). Additionally, it can be seen in figure 2.1, the recovery performance can be between 4% and 6% strain level.

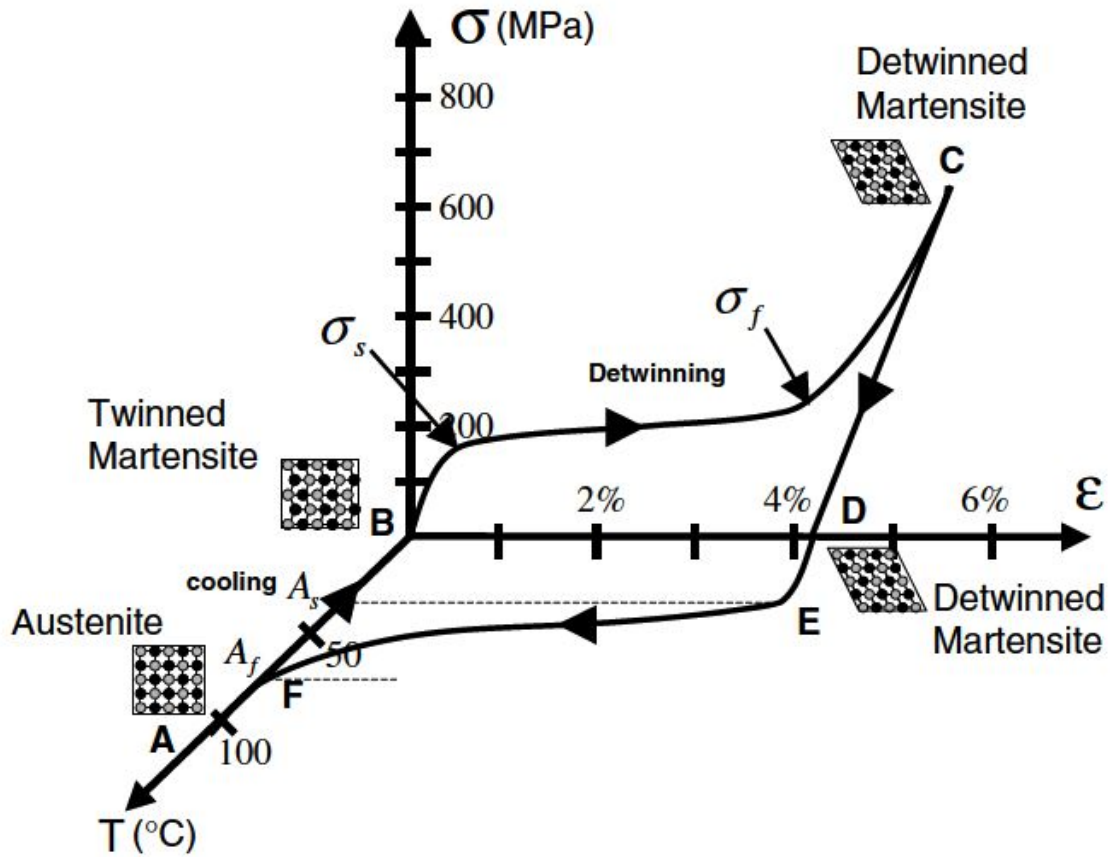


Figure 2.1 SMA behaviour in stress-strain-temperature space [2]

### 2.1.1. Shape Memory Alloy Wires

SMA materials have high energy density. In other words, they can recover the high actuation stroke or strain created by high actuation load or stress. As can be inferred from the dashed line on figure 2.3, an SMA can produce much work though its low volume. Therefore, SMA wires are widely used in actuator designs because of their compactness.

They can be produced in different diameters and as having phase transition temperatures dependent on the composition of the elements in figure 2.4.

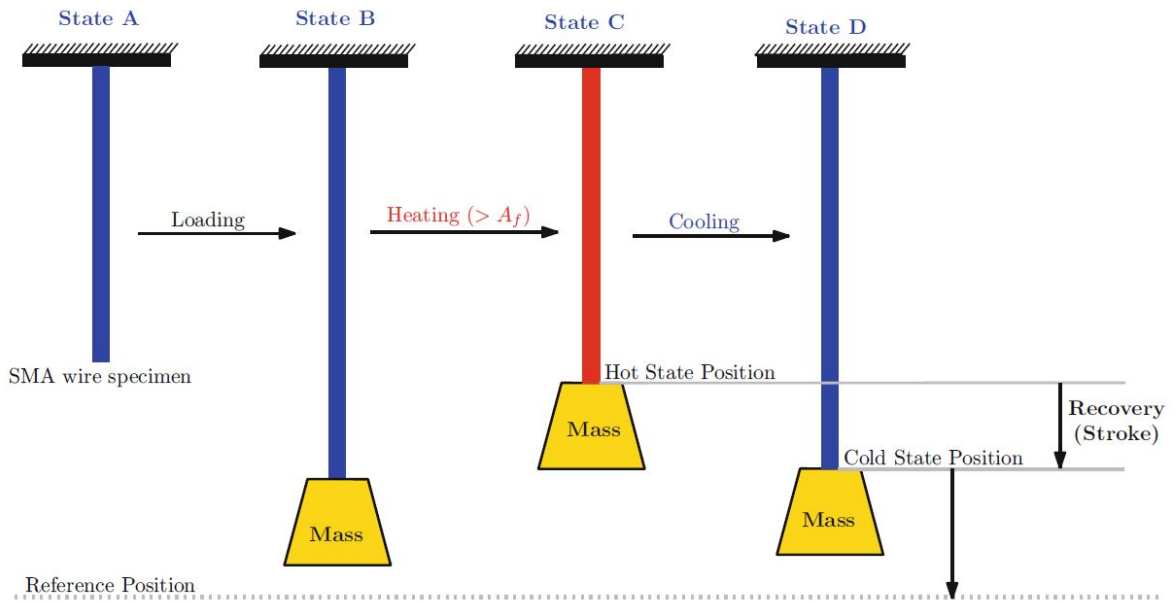


Figure 2.2 SME in an example [3]

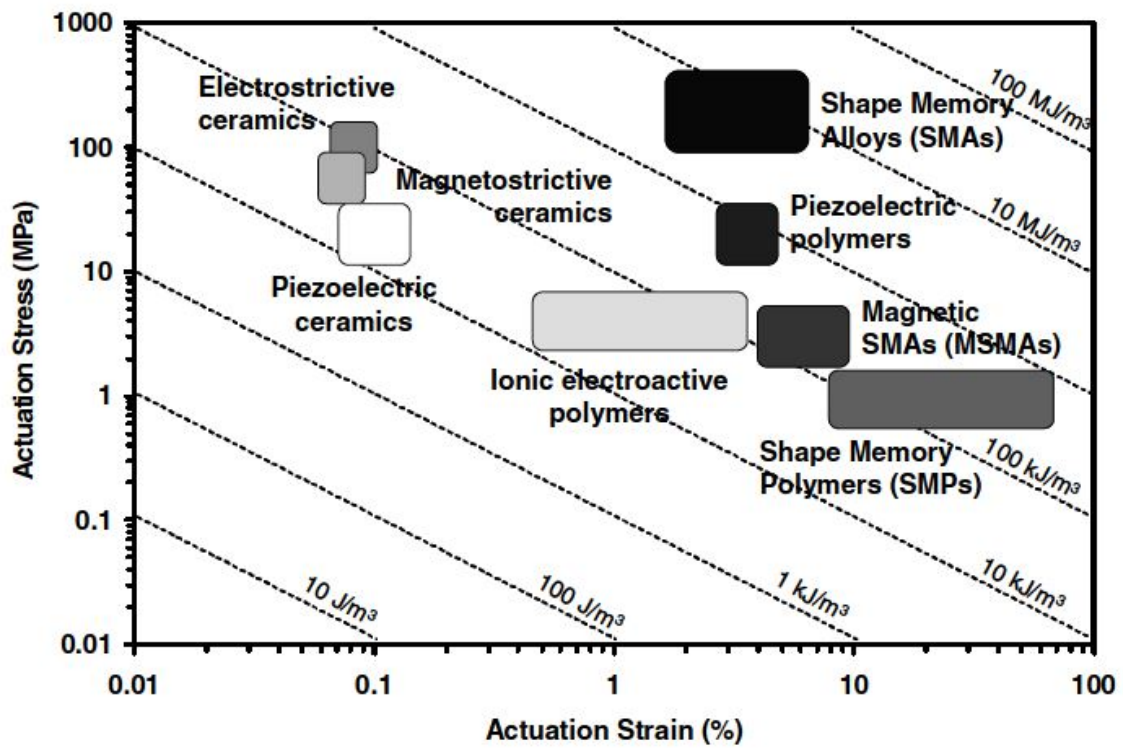
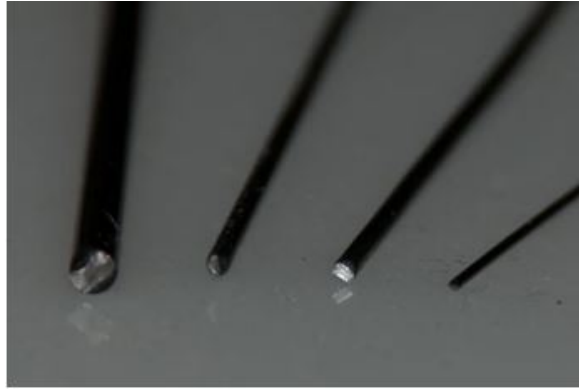
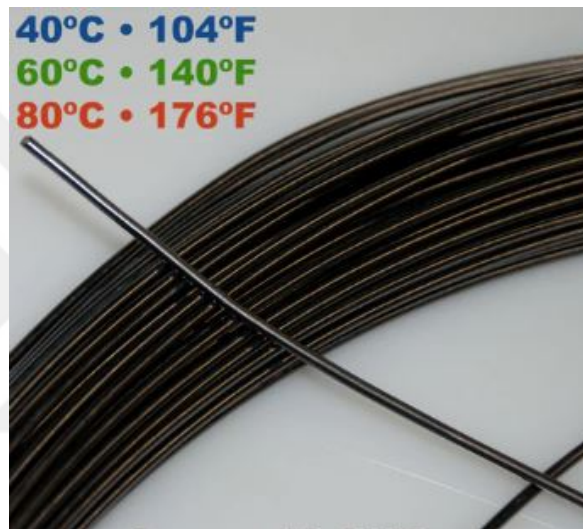


Figure 2.3 Energy density and actuation performance of SMAs [2]



(a)



(b)

Figure 2.4 [5] SMA wires in different diameters (a) and phase transition temperatures (b)

### 2.1.2. Modeling of Shape Memory Alloys

SMA materials exhibit thermomechanical properties as mentioned. In other words, they change phases during heating or cooling and thus, they produce mechanical effect due to the strength difference between martensite and austenite phases. This phase transition has hysteresis like in figure 2.1 or in figure 2.5. The temperatures that the austenite phase start and finish are different from the temperatures that the martensite phase starts and finishes. Moreover, these transition temperatures shift to higher temperatures with increasing loading, i.e. depend on stress as well, as can be seen in figure 2.5.

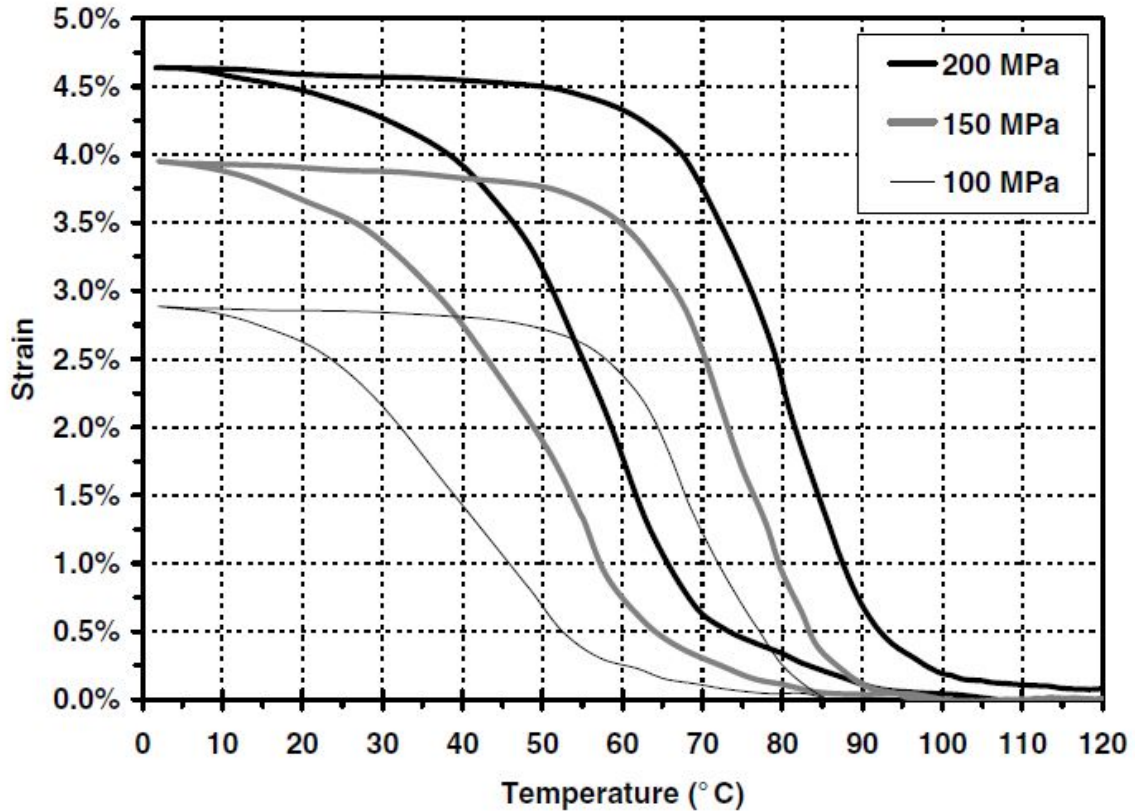


Figure 2.5 Transformation behaviour in NiTi under changing stresses [2]

Another phenomenon about SMA behaviour is the creation of minor loops [6, 7]. As can be seen in figure 2.6, if a phase transition is not completed yet (if completed, this is defined as major loop under any loading), minor loops start to occur due to passing to cooling while heating or to heating while cooling.

At the beginning of modeling, consideration of only convection is seen mostly enough to create heat transfer model, particularly for SMA wire. In this case, the length and thickness of the wire are low enough to take into account conduction and the temperatures that SMA wires operate are low enough to take into account heat transfer by radiation as well [7, 8]. Therefore, heat transfer model is generally given with convection terms by ignoring radiation and conduction [7, 9–12]. This model can be improved by adding the latent heat term. A certain part of thermal energy is used for phase transition and contribution of the energy to the heat decreases though continuing to be given. Thus, the latent heat is considered in some studies [10, 11]. Joule heating is commonly the method used to heat the SMA wires

[7, 9–11, 13, 14]. The enhancement of the actuation response of an SMA wire through its thermo-mechanical properties is still a common and current research subject [11]. Recently, applications such as reinforcement by SMA wire embedded with secondary materials to create composite structure designs have gained popularity [15, 16]. Considering that the mechanical properties of the secondary material in the composite structures change with heat, thermal modeling becomes even more important. Moreover, the cooling process becomes important for two-way actuation designs. The desire to increase the actuation frequency has brought the implementation of different cooling techniques [12, 17]. However, the simplest and most common practice is still air, either natural or forced convection. Although, the convection coefficient is able to increase up to eight times by creating variable air flow by using cooling methods such as a fan [17], it also adds complexity and cost to the actuator system.

Many models describing hysteresis during phase transformations have been suggested from the simple one to the more complex. While [18] models the phase transformation by using an exponential function dependent on phase transition temperatures for a major loop, [6] inserts minor loops into the model by defining two additional parameters for the offset and shifting. Two model approaches can be improved by considering the stress and also variable stress [7, 19].

Considering this behaviour, modeling of SMA materials becomes complex. Therefore, many constitutive models involved thermal input, phase transformation and eventually mechanical response have been suggested from over the past two decades to the present [20–23]. Moreover, there are studies in which SMA materials are modeled by using finite element analysis software or writing subroutines [24–26].

## **2.2. Parameter Estimation**

Scientists want to construct a model to describe the relation between the data if there are some data obtained from the observation of a certain system in their hand. Thus, they try to predict the responses of the system under repetitive or variable excitations and then, they can use

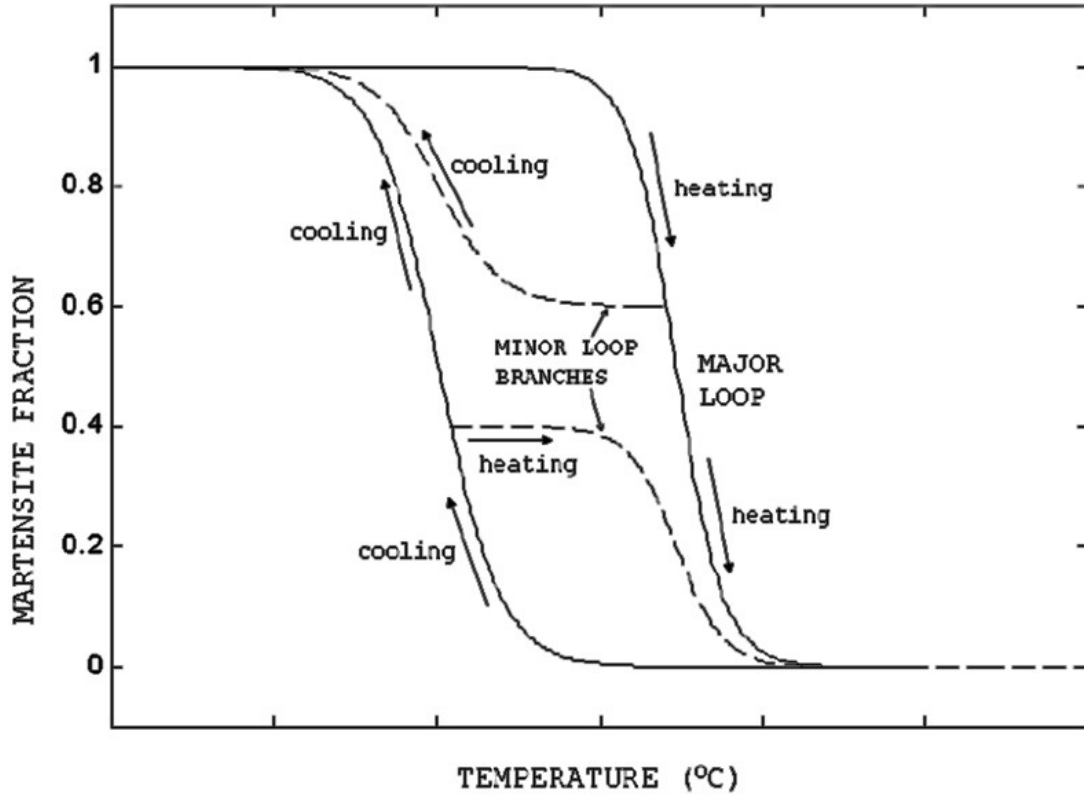


Figure 2.6 Minor loops in major hysteresis loop [7]

or control the system. Mathematical models derived for this have some parameters. These can have physical meanings such as material properties or can also be just a mathematical expression or a factor. The parameters can be found empirically. Besides, they can be estimated by using some mathematical approaches with a certain part of the data. The diagram of this method called as parameter estimation or system identification is given in figure 2.7 [27].

The parameters of the actuator model are predicted by using gray box and mutable smart bee algorithm in [28]. The prediction methods give no physical parameters such as specific heat, latent heat or convectional heat transfer coefficients. They give the parameters of the model describing the actuation behavior except phase transformation temperatures. In [29], Hammerstein-Wiener model is identified using the MATLAB System Identification Toolbox between pulse width modulation (PWM) current input data and temperature output data; also, between temperature input data and position output data.

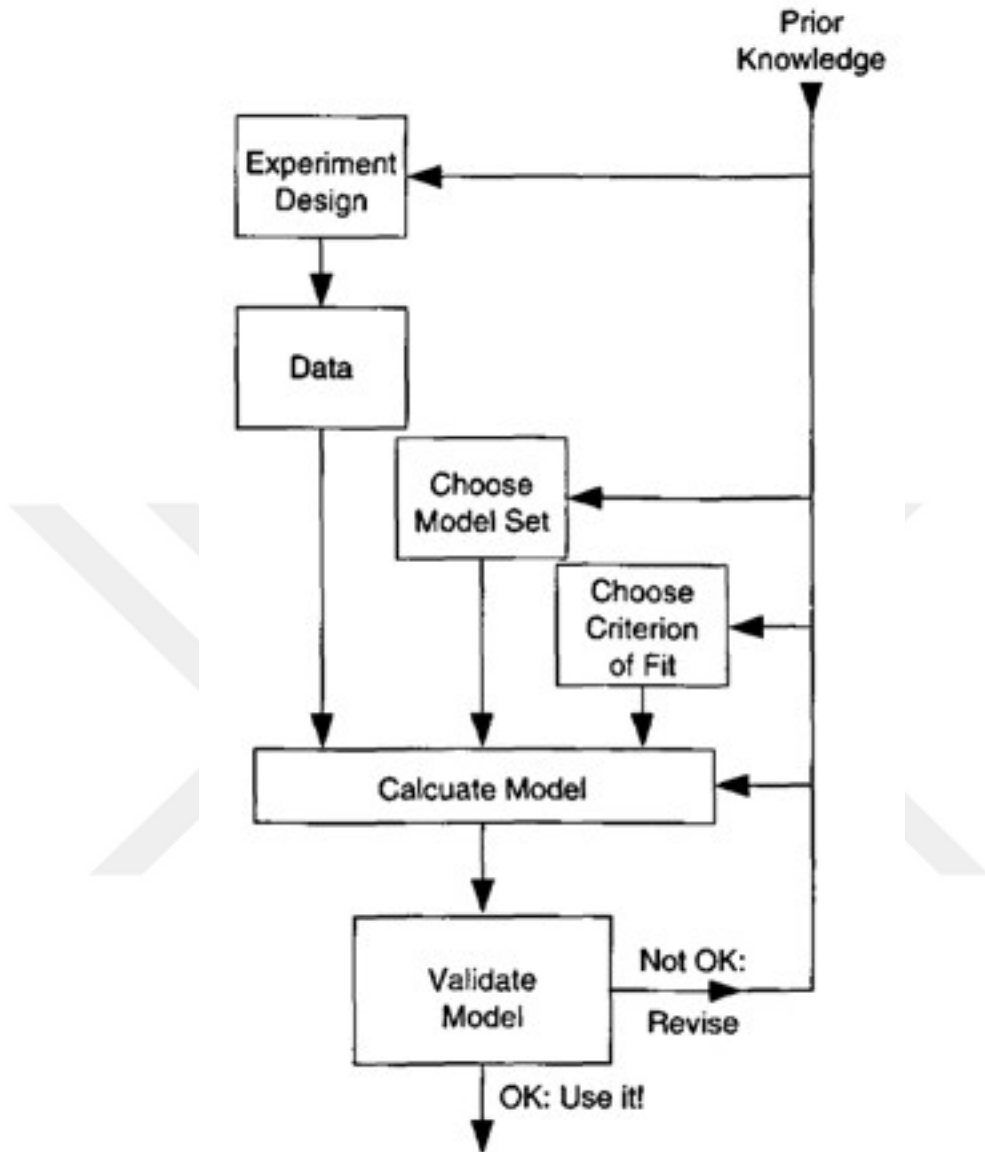


Figure 2.7 The system identification loop [27]

The proportional-integral-derivative (PID) control algorithm is implemented along with the developed model which gives satisfactory results for the actuation. In this study, the identification is applied to determine the transfer functions not to determine physical parameters of the heat transfer model. Identification is carried out by genetic/gradient-based optimization algorithm in [30, 31]. The Levenberge Marquardt algorithm is utilized to solve the inverse problem and applied to identify the non-linear constitutive parameters of superelastic SMAs.

In [32], parameters of a phenomenological model of the SMA are estimated by using Unscented Kalman Filtering Method. The SMA wire phenomenological model is constructed with three nonlinear state equations. The constant parameters defining these equations are estimated. In these equations, convection coefficient and specific heat parameters stay in the non-linear states as embedded and latent heat is not modeled. Ambient temperature and convection coefficient are taken into account as uncertain parameters, because they depend on variant environmental circumstances.

In [33], recursive least-squares (RLS) algorithm is used to estimate parameters coming from a nonlinear model that is similar to the SMA hysteric characteristics which is suggested.

## **2.3. SMA Actuators**

Since shape memory alloy (SMA) wires are light, take up little space and a high energy density for the drive, they have started to be utilized as smart actuators in many engineering applications [34]. They are used in a wide variety of engineering applications and study areas: in aircraft technologies and morphing structures [35–37], in bio-mechanical/bio-medical applications [38–40], in civil structures for structural safety as vibration damping or reinforcement element [41–44], in robotics and control [45] also in soft robotics [46], in miniature applications [47, 48] and for some other practical applications such as soft wearable robots [49, 50]. Some images are given in figure 2.8 and figure 2.9 as examples of the applications of SMAs.

### **2.3.1. SMA-Based Soft and Composite Actuators**

A new combined structure may be designed using a material to provide actuation like an SMA wire and a secondary material having soft property like a polymer. These kinds of designs are called as soft composite structures. Soft actuators have been used widely in many areas because of their flexibility and compactness. Thus, the soft actuation concept can be encountered in many different applications [51, 52], such as soft robots, bio-inspired

robots [53–56], artificial muscles [46, 57, 58], morphing structures [59], microrobots [60], soft wearable designs-robots [49, 61, 62] or soft grippers[46, 63, 64], origami structures [64–66].

Soft actuation can be provided by using a soft material like shape memory polymer (SMP) [70, 71] or integrating an actuator material like an SMA wire [72, 73] to any soft body. The integration can be carried out by different methods such as molding, curing [74, 75] or 3D printing [16, 56, 60, 76–79]. The stiffness properties of the composite structure obtained by embedding SMA wires in the acrylic mold have been studied in [80]. Woven glass/epoxy structure is reinforced by using SMA wire in [81]. Macroscopic mechanical properties of the composite obtained by curing are investigated.

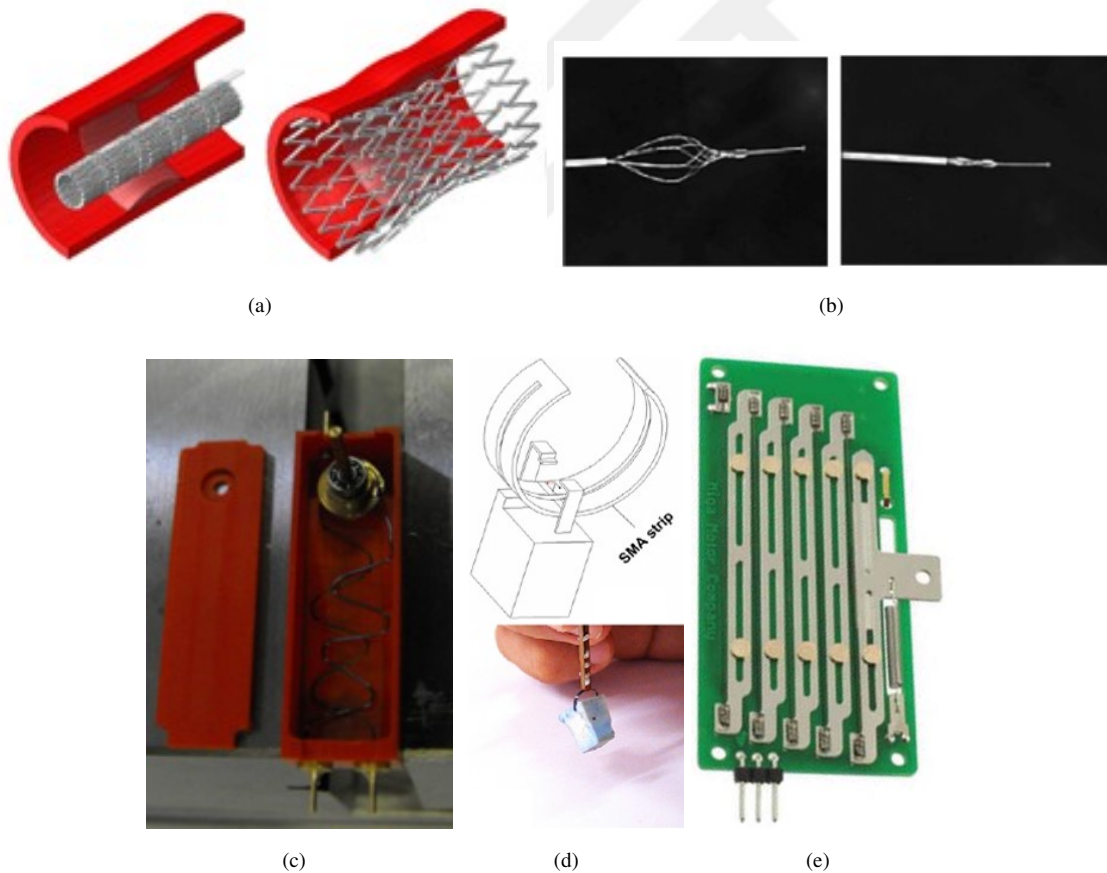


Figure 2.8 Self-expanding Nitinol stent [67], (b) Nitinol retrieval basket [67], (c) Mini rotational actuator activated by two antagonist snake-like NiTi wires [68],(d) a gripper type actuator [34] and (e) a linear bias-type cascaded actuator [69]

Especially, 3D printing has become an increasingly popular method by providing simple, fast and low cost fabrication. Meanwhile limitations related to usage of soft materials in 3D printing and ability to produce complex structures compared to molding techniques are explained in [76].

There exist many studies which investigate the actuation performances, mechanical properties and control of composites. In [82], hybrid composite beams based shape memory alloys are created with carbon fiber-reinforced polymer. The composite structure can be controlled by PID controller by feeding the self-sensing deflection signal coming from the relation between relation SMA resistance and deflection of the structure. SMA material is embedded into soft polymers produced by using 3D printer in [77]. In this study, the effects of the variable stiffnesses obtained by changing thickness and type of the soft structure are investigated to provide large and reversible deflection. In [16], an SMA wire is embedded between Nylon 12 filament and flexible Polylactic Acid or polylactide (PLA) layers printed by 3D printer. The shape memory composite is reversible. In [83], composite beams are produced by embedding SMA wires into glass/epoxy and carbon/epoxy materials. Prestrain is applied to the SMA wires. Actuation strokes based on bending are studied. In [78], the SMA wire has U-memorized shape. After prestrain is applied to flatten the wire, 3D printing is used to obtain soft actuator composite. In [79], SMA spring is used as an actuator. The body produced by 3D printer is inspired of crawling motion of an inchworm. After actuation, the energy stored in the TPU body mobilizes the crawling robot. In [84], a composite structure is created by woven fiberglass and SMA actuator to act as a morphing structure. A composite structure in [85] is created for a kind of soft robot. An origami structure is driven by shape memory alloy (SMA) springs as well to make the robot jump or walk. Some images are given in figure 2.10 and figure 2.11 as examples of SMA-based soft and composite actuators.

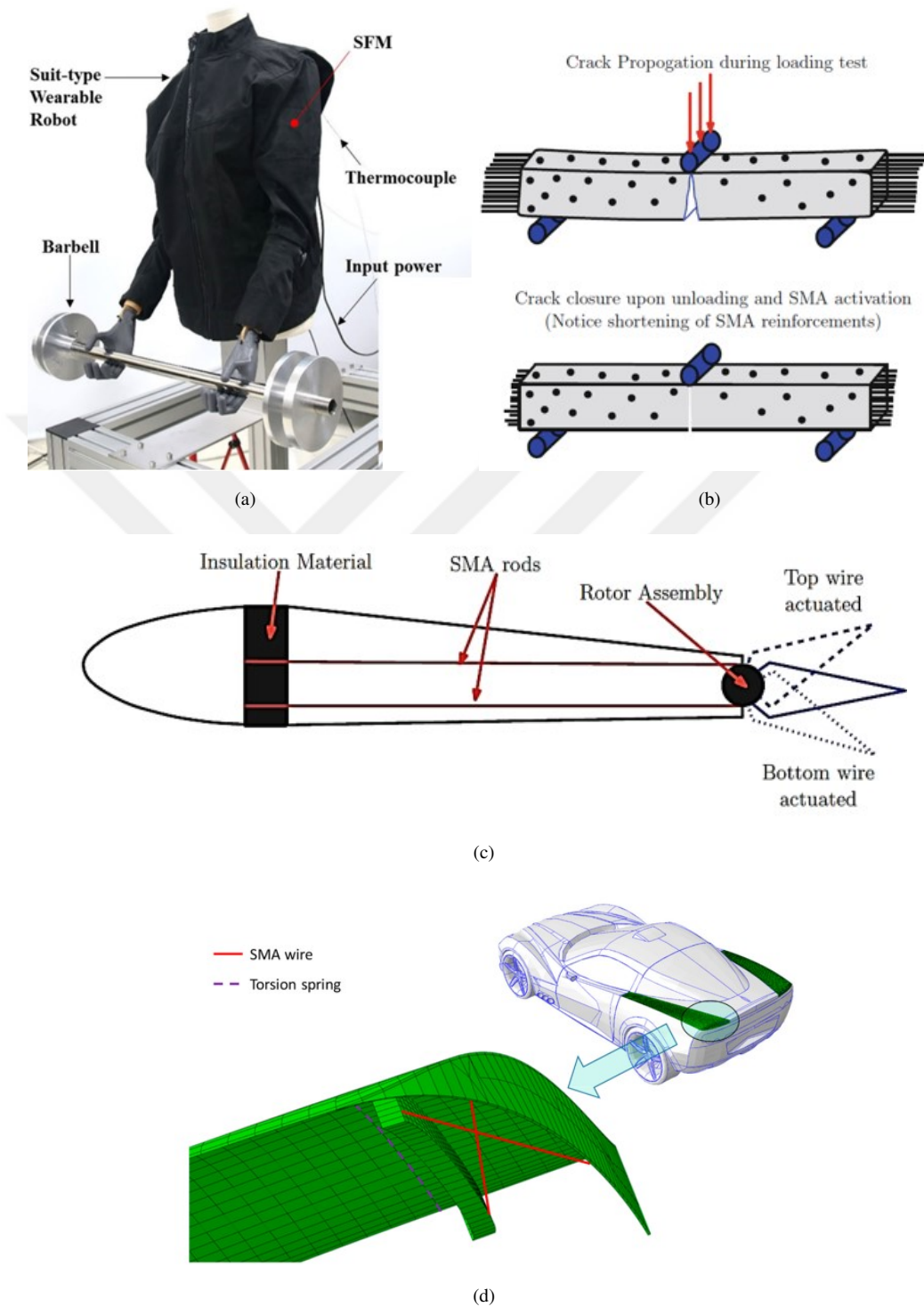


Figure 2.9 (a) shape-memory-alloy-based fabric muscle (SFM) as an actuator and phase transition temperatures [50], (b) SMA reinforcements in a concrete block with an initial crack [3], (c) The use of pretwisted SMA rods to torsionally actuate blade tabs [3] and (d) morphing example in automotive [37]

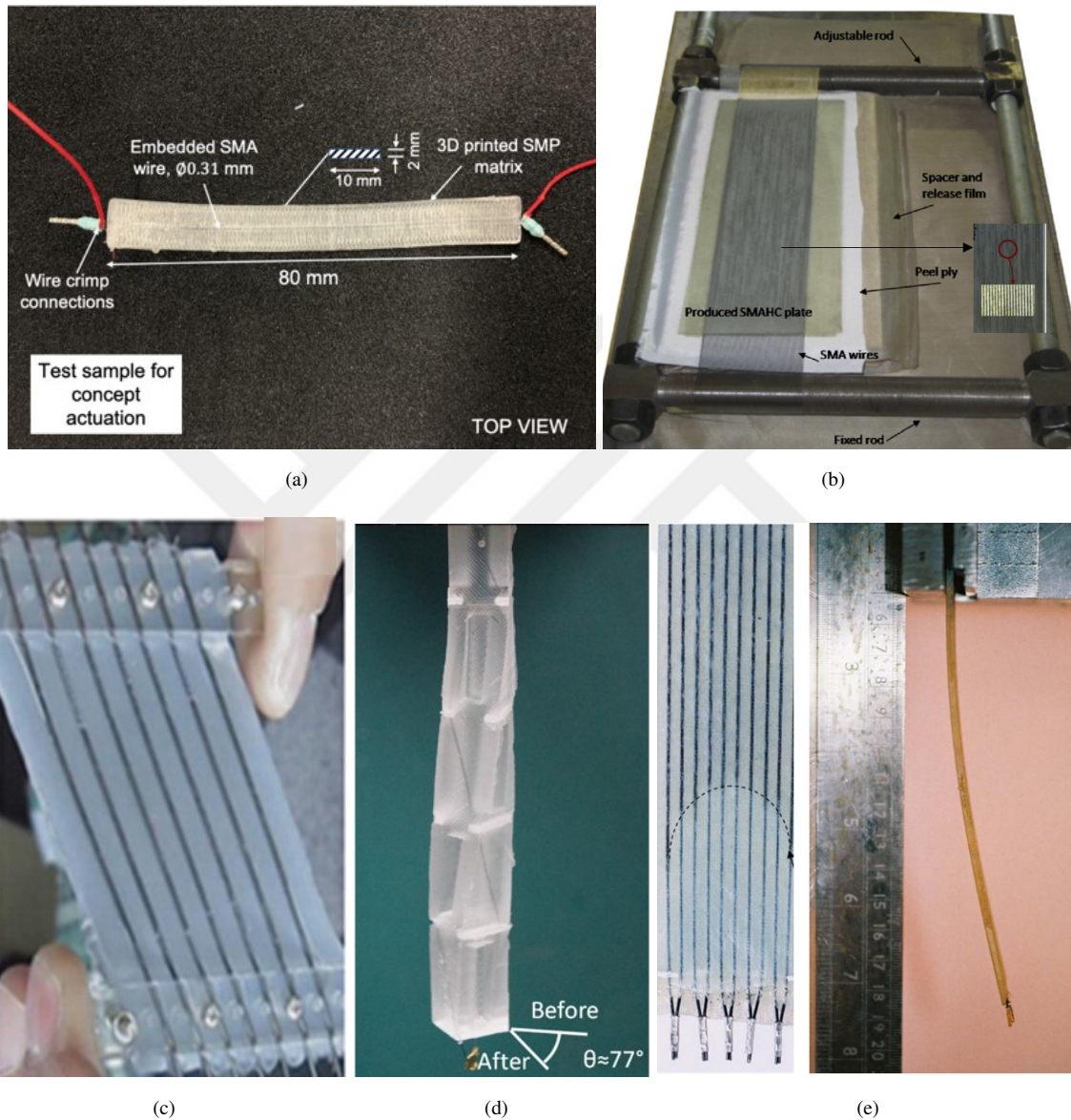
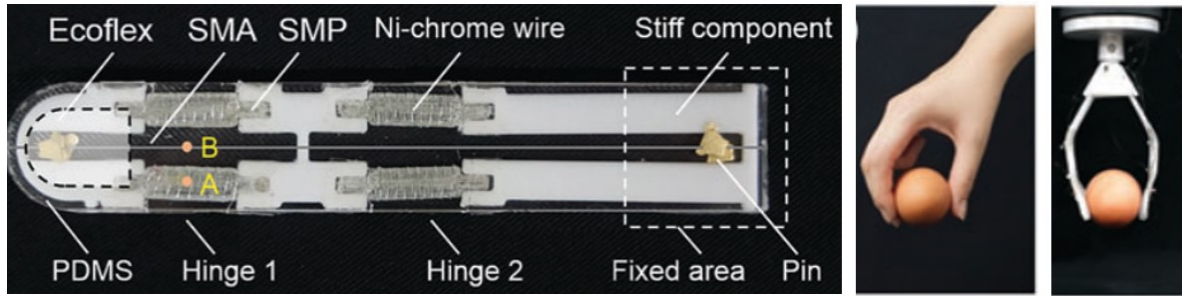
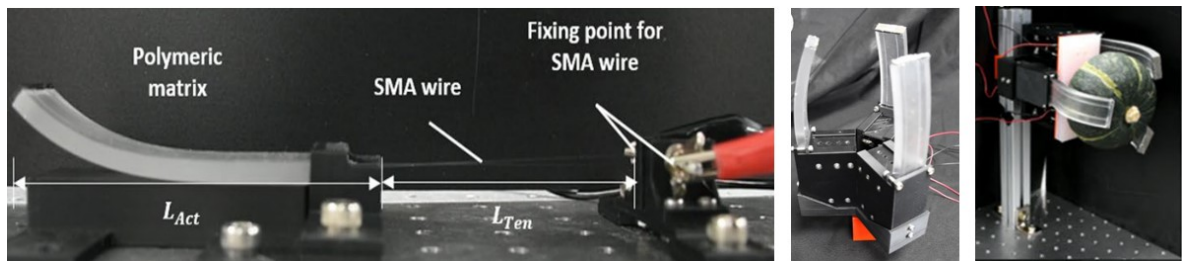


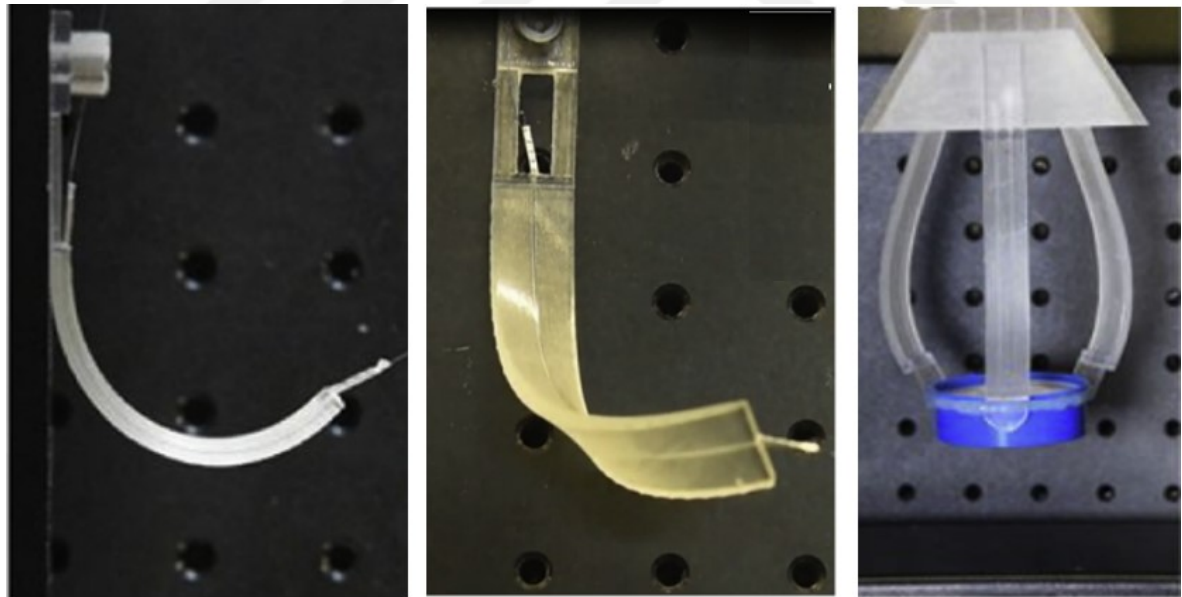
Figure 2.10 (a) A Bi-State Shape Memory Material Composite Soft Actuator [78], (b) a shape memory alloy hybrid composite (SMAHC) plate [81], (c) multi-functional composites using elastomer embedded with Shape Memory Alloy wires [80], (d) SMA-based twisting soft actuator [75] and (e) composite beam embedded with SMA wires [83]



(a)



(b)



(c)

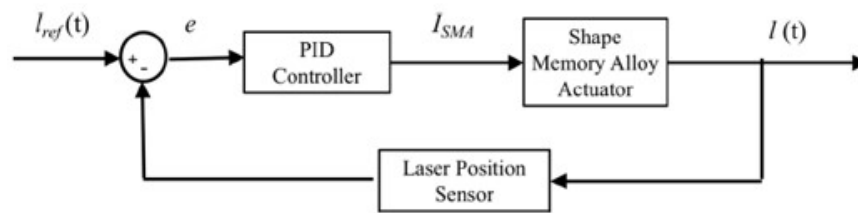
Figure 2.11 (a) Shape Memory Alloy-Based Soft Gripper [46], (b) Long Shape Memory Alloy tendon- based Soft Robotic Actuators [63], (c) a rubber-like elastomer, 3D printed soft actuators powered by SMA Wires [76]

## **2.4. Control of SMA wires and Actuators**

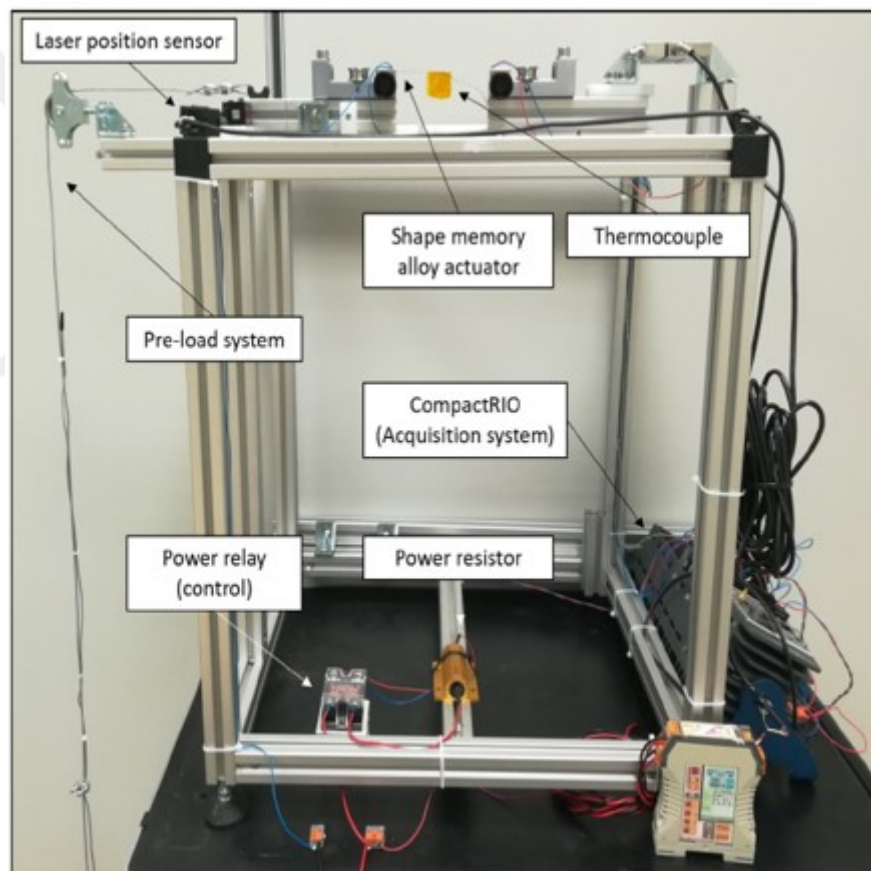
Basically, SMA wires or SMA based actuators can be controlled by using strain feedback [86–90]. A common experimental setup and a diagram for SMA wire strain control are given in figure 2.12. Also, temperature feedback can be used to control [88, 91], although temperature measurement can be difficult on SMA wires due to low surface area to connect a measurement device like thermocouple. The reference signals can sometimes be determined with respect to the actuation system that SMAs are used and the feedback signals, for example, can be displacement or angular position [14, 92–96].

Model based controller design or using controller tuning methods according to the desired controller performance parameters such as settling time, rise time etc., can be difficult because SMA based actuators exhibit nonlinear responses and hysteresis. PID type controllers [82, 84, 87, 88, 94, 95, 97–101] have been frequently preferred and many controller design methods have been implemented for robustness [86, 90–93, 96].

Additionally, self-sensing method [82, 87, 95, 97–99] can give good control performance without directly displacement measurement, by utilizing almost linear relation between resistance and strain.



(a)



(b)

Figure 2.12 [87] Control diagram (a) and a common experimental setup for SMA wire control (b)

### 3. SMA WIRE MODELING

The SMA materials exhibit thermo-mechanical property. They change their phases from martensite to austenite by heated or vice versa by cooled. While they are changing their deformed shapes towards the original shapes under heat, they produce mechanical response. These three phenomena, i.e. heating, phase transition and mechanical response, need to be considered, if a model is derived for an SMA material or an SMA wire like in this study. Thus, heat transfer model, phase model and mechanical model are mentioned in section 3.1., section 3.2. and section 3.3., respectively.

#### 3.1. Heat Transfer Model for The SMA Wire

Joule heating is a common preferred method to heat SMA wires in the literature. Accordingly, the equation of conservation energy depicted in figure 3.1 is given in equation (1) as follows [10] and the terms of the equation are bulleted in table 3.1.

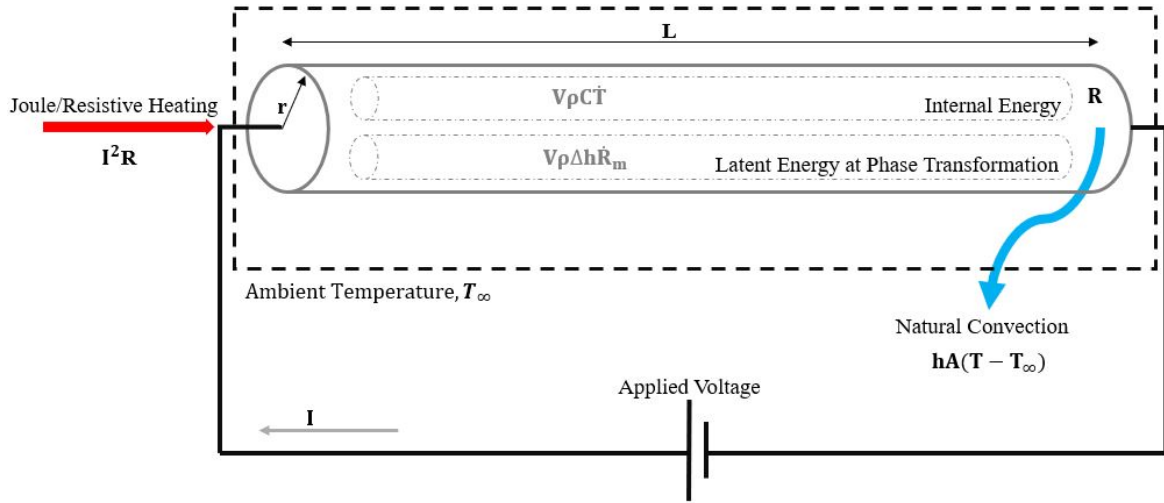


Figure 3.1 Resistive heating and SMA heat transfer model

$$V\rho C\frac{dT}{dt} - V\rho\Delta h\frac{d\xi}{dt} = I^2R - hA(T - T_\infty) \quad (1)$$

Table 3.1 Heat transfer model terms for the SMA wire

| Term                           | Name                        |
|--------------------------------|-----------------------------|
| $V\rho C\frac{dT}{dt}$         | Internal energy of the wire |
| $V\rho\Delta h\frac{d\xi}{dt}$ | Latent energy               |
| $I^2R$                         | Electrical power            |
| $hA(T - T_\infty)$             | Natural convection          |

The heat transfer model of the SMA wire is based on resistive heating where the electrical current raises the temperature of the wire. On the other side, convection from the wire surface area results in a heat loss. The convection term models the major part of the rate of change of temperature that is proportional to volume ( $V$ ), density ( $\rho$ ) and specific heat coefficient ( $C$ ) of the SMA wire. Moreover,  $I$ ,  $h$ ,  $T$  and  $T_\infty$  are input electrical current, heat transfer coefficient, wire temperature and ambient temperature, respectively.

During phase changing from martensite to austinite or vice versa, there is another term that have contribution for the rate of change of temperature. This term is the latent heat with the latent heat coefficient,  $\Delta h$ . The latent heat or latent energy term models the part of the rate of change of the phase or martensite fraction that is proportional to  $V$ ,  $\rho$  and  $\Delta h$ .

There are some assumptions related to equation (1). Firstly, compared to convection, firstly radiation is negligible in the operating temperature range and secondly, conduction can be ignored because the wire is short and thin enough; is uniform along its length and cross section. Specific heat and heat convection can be modeled as temperature dependent [99, 102]. Furthermore, the electrical resistance changes due to the heating and changing in cross section and length of the wire. In this study, changing in the parameters such as the volume  $V$ , wire surface area  $A$  (contribution of cross-sectional area is very small and negligible) are assumed to be negligible. The change of the electrical resistivity is also assumed to be negligible, because the phase transformation is very rapid in where the resistivity can change [10]. Thus, the electrical resistance,  $R$  is taken as constant.

Heat transfer model is the first part of the complete thermomechanical expression of an SMA wire and related to the phase model with the latent heat term. Therefore, heat transfer model parameters are important to improve a complete model. These parameters can not always be given by any manufacturer which the SMA wire is supplied. A method will be suggested to obtain the parameters in section 4..

### 3.2. Martensite Fraction Phase Model

SMA materials are known to switch between the two phases: martensite and austenite phases depending on the temperature.  $\xi$  named as martensite fraction is a unitless variable between 0 and 1. The martensite fraction defines the extent of the transformation between the phases. The martensite fraction value of 1 means that it is fully martensite and zero means that it is fully austenite; in other cases, the material is both martensite and austenite in different levels. The experiment is conducted at the room temperature. Phase transition temperatures are above the room temperature for the specific SMA wire used in this study (as it can also be seen in figure 3.5). Hence, first at room temperature, the wire is in the twinned martensite state. Then, after loading, still at room temperature, the wire outstretches to the detwinned martensite state. When heated above the austenite start temperature and up to austenite finish temperature, the wire transforms from the martensite phase to the austenite phase. At that point, the strain generated during loading, is recovered. The wire goes back to the twinned martensite form while cooling from martensite start temperature to martensite finish temperature.

SMA materials do not complete the heating and cooling cycle along the same path; they exhibit hysteresis as shown in figure 3.2. Thus, usage of two different models can be a good alternative for austenite phase change temperatures for heating action and martensite phase change temperatures for cooling action. In this study, Ikuta model is selected [18] for the hysteresis model because of its simplicity. Ikuta hysteresis model fits two exponential functions to the phase changes in heating and cooling. These functions depend on the phase transformation temperatures and the wire temperature:  $A_s$ ,  $A_f$ ,  $M_s$ ,  $M_f$  and  $T$  are

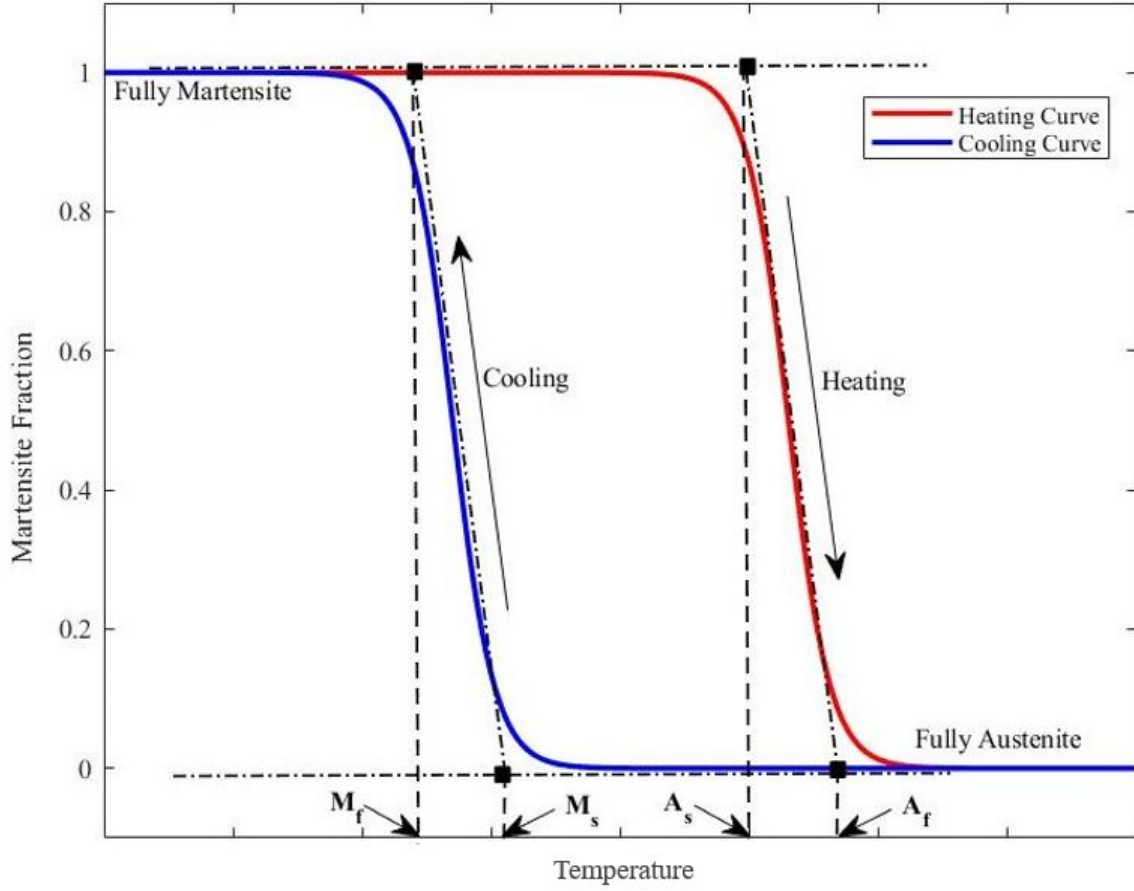


Figure 3.2 Hysteresis loop and transformation temperatures of an SMA material

austenite start, austenite finish, martensite start, martensite finish temperatures and the wire temperature, respectively. The common function is given in equation (2) and  $\xi$  represents the martensite fraction. The cooling exponential function is derived from equation (2) by using equation (3) and equation (4). The heating exponential function is derived from equation (3) again but by using equation (5) and equation (6) in this case.

$$\xi(T) = \frac{1}{1 + e^{k_m(T-T_{0m})}} \quad (2)$$

$$k_m = \frac{6.2}{M_s - M_f} \quad (3)$$

$$T_{0m} = \frac{M_s + M_f}{2} \quad (4)$$

$$k_m = \frac{6.2}{A_f - A_s} \quad (5)$$

$$T_{0m} = \frac{A_s + A_f}{2} \quad (6)$$

### 3.3. Transition to The Mechanical Model

Considering induced maximum strain, i.e. major loop, under a certain preload, it can provide transition to the mechanical model from phase model. This can be expressed as in equation (7).

$$\varepsilon(T(\sigma)) = \varepsilon_{max}\xi(T) = \frac{1}{1 + e^{k_m(T-T_{0m})}} \quad (7)$$

### 3.4. Experimental Detup and Characterization Procedure

All parts of the thermo-mechanical model are based on Ikuta phase model according to equation (1) and equation (7). Also, Ikuta phase model is involved phase transition temperatures. These temperatures need to be characterized by an experiment.

#### 3.4.1. Experimental Setup

A custom-build characterization experimental setup is used to perform the actuation experiments. A diagram for entire measurement and control procedure is given in figure 3.4. Furthermore, picture of the experimental setup is shown in figure 3.5. Material properties and dimensions of the SMA wire are given in table 3.2. The wire is a nickel-titanium alloy (Nitinol) wire of Nexmetal brand [5].

In the experiments, the wire is stretched by hanging a dead weight of 3.5 kg (equivalently 125 MPa stress) at its free end. It has been observed that the hysteresis behavior of the wire becomes clear under the stresses around 125 MPa. Also, more load causes shifting of the hysteresis character of the wire to higher temperatures because more current must be given to

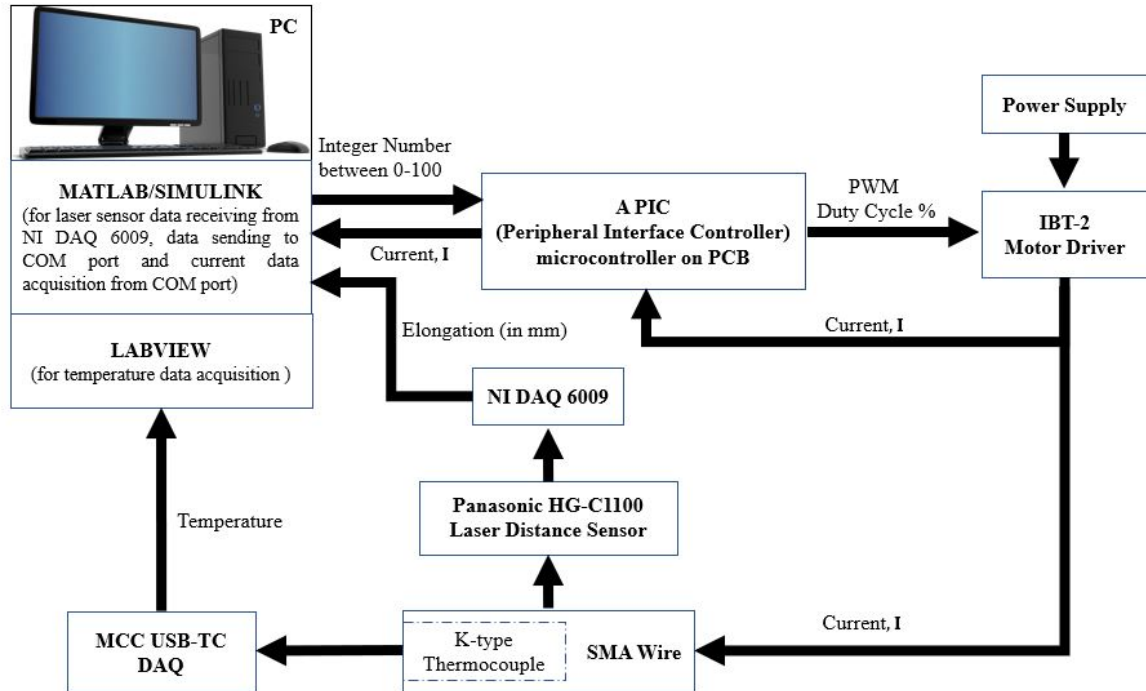


Figure 3.3 Characterization procedure

recover from the greater strain provoked by more loading. The current going towards 1 A and higher temperature damages the SMA wire and the other connection wires in the experiment. Thus, 125 MPa loading, in other words, dead weight of 3.5 kg has been used. This free end of the wire is passed over a pulley. The friction on pulley is evaluated as negligible and its surface is lubricated as a measure against the friction. The other end of the wire is fastened to the intermediate rigid component on 3-axis linear stage (Thorlabs, 3-axis RollerBlock). A 3-axis load cell (Kistler 9317C) with an amplifier (Kistler 5037A) is connected between 3-axis linear stage and the intermediate rigid component. The wire is precisely positioned just on the longitudinal axis by adjusting with the linear stage in all the axes while observing the force at each axis. A single axis load cell is sufficient for this study; however, it could be seen that there was no load on the other two axes by additionally using 3-axis load cell.

An aluminum foil material as a reflective surface is fixed at the free end of the wire and in front of the laser displacement sensor (Panasonic HG-C 1100) for the sensor beam. The displacement sensor measures the change of the length of wire. Then the engineering strain is calculated by dividing by the original length of the wire. For Joule heating, a motor driver

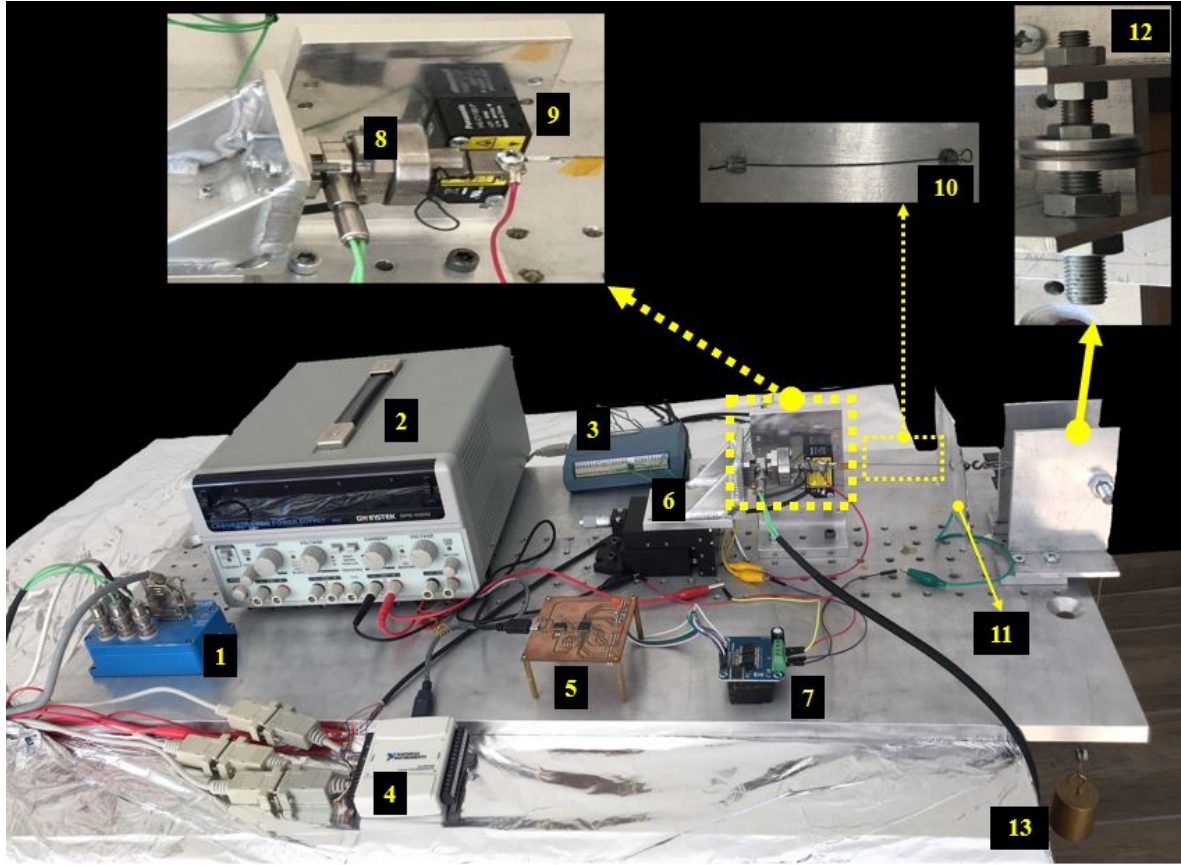


Figure 3.4 Experimental setup.1: amplifier, 2: power supply, 3: thermocouple DAQ card, 4: DAQ board, 5: electronic circuit, 6: 3-axis linear stage, 7: motor driver, 8: 3-axis load cell, 9: laser displacement sensor, 10: SMA wire, 11: reflective surface combined with SMA wire, 12: pulley, 13: dead weight, 14: thermocouple connection with kapton tape

(IBT-2) is used to supply electrical current where the master command is given from the MATLAB to the PIC microcontroller. This device generates the PWM signal which controls the power supply to apply an approximately 300 mA electrical current for each increase in the % duty cycle. IBT-2 and PIC connections are on a dedicated printed circuit board (PCB). Finally, a K-type thermocouple is connected to the wire by a Kapton tape. In this

Table 3.2 Dimensional and material properties of the SMA wire

| Parameters | Symbol | Value | Units           |
|------------|--------|-------|-----------------|
| Diameter   | D      | 0.5   | mm              |
| Resistance | R      | 1.34  | $\Omega$        |
| Density    | $\rho$ | 6450  | $\text{kg/m}^3$ |

way, not only the contact between the small diameter wire and thermocouple is ensured but also thermal isolation is provided against the interference of the measurement with the environment. The temperature data are sent to Labview user interface by a data acquisition card (MCC USB-TC DAQ).

The experimental setup on the horizontal axis has been preferred since it is easy to observe the experiment while running. This kind of SMA wires have the stroke from 3% up to 8% of their lengths, dependently on the load [103–106]. The wire is contracted approximately 5% of its length. This means the pulley causes no considerable loss of the wire stroke, because this percent value stays between 3% and 8%. Also, the value of 5% can be observed as the result of repeated loading cycles. In other words, any subsequent loading cycle is approximately settled to this value as well.

#### **3.4.2. Characterization of The SMA Wire**

The SMA wire characterization procedure is performed to determine the phase transformation temperatures,  $A_s$ ,  $A_f$ ,  $M_s$  and  $M_f$ . If any information is not given in a manufacturer specification sheet about these temperatures, there are two recognized methods [2, 107–109] to estimate the temperatures: the first method is based on direct determination by using differential scanning calorimetry (DSC) under heat flow, while the other method is based on making the characterization using a dedicated experimental setup. Here, the second method is adopted. In the first method, the measurement principle detects the change of the phase with the temperature utilizing a thermo-analytical technique. However, the martensite fraction is not easily obtained from the measurements and loading the sample during the measurement cannot be achieved. Since strain can be measured by using a displacement sensing device with sufficient accuracy, curve of the temperature vs. strain is easier to acquire in the former method. In this work, divided by the maximum reachable strain value under loading, temperature vs. strain curve is scaled to temperature vs.  $\xi$  curve. Additionally, the time rate of change of martensite fraction,  $\dot{\xi}$ , is needed to complete the heat model. Thus, the transformation from strain to martensite fraction,  $\xi$ , should be done. The

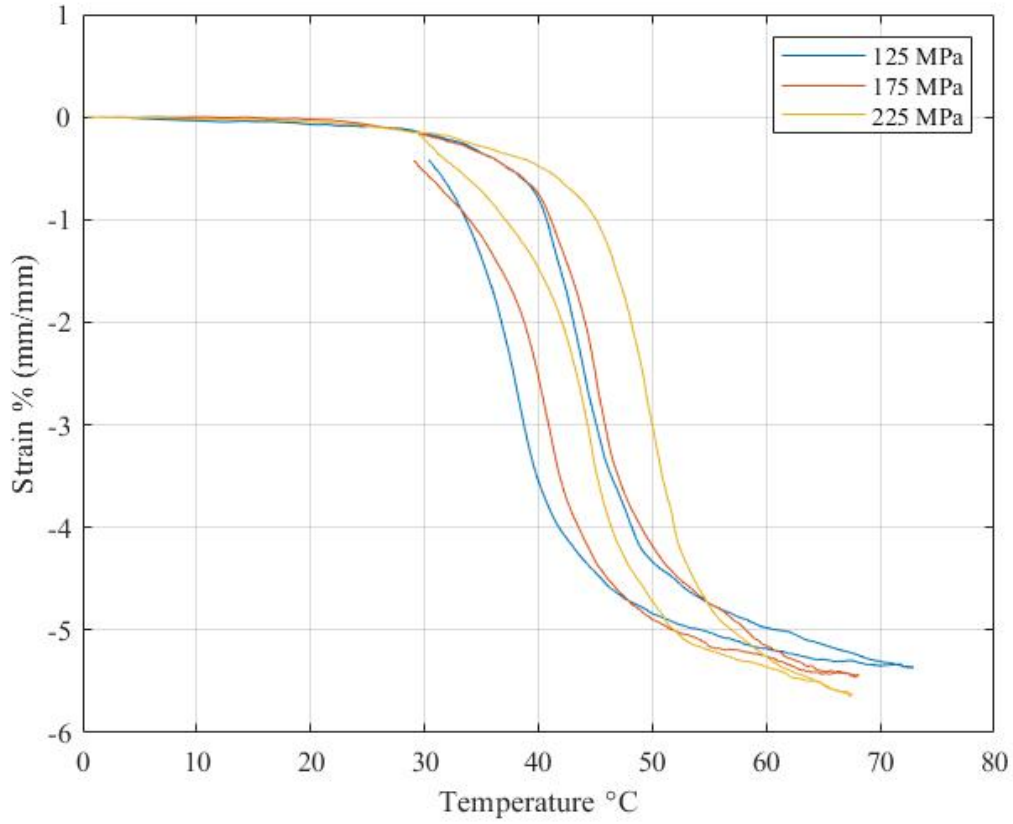


Figure 3.5 Experimental hysteresis and shifting of transformation temperatures with increasing stress

details are given in Section "Determination of temperature- $\xi$  curve and phase transformation temperatures". Furthermore, there is a load dependency on the phase transformations. For instance, the temperature vs. strain (similarly, temperature vs.  $\xi$ ) hysteresis curve shifts towards higher temperatures to change phase with raising load as shown in figure 3.5. The ambient temperature is  $T_{\infty} = 27.2^{\circ}\text{C}$  for this particular experiment which is the starting temperature.

### 3.4.3. Effect of Fast Heating/Cooling

SMA material exhibits another compelling behavior for the actuation applications under fast heating/cooling action. For instance, change in the hysteresis and transformation temperatures according to figure 3.6 and figure 3.7 are shown in figure 3.8 for different

rate of temperature increments. Although martensite fraction is theoretically limited by 0 and 1, disturbances during the data collection are causing a deviation out of this range. The hysteresis behavior as well as the transformation temperatures is highly effected if the rate of the temperature change is high due to the electrical current. Similar observations are done in the DSC experiments as well [110, 111]. Hence, variations in transformation temperatures are essential to be determined, especially for fast heating/cooling case which shows the importance of in situ parameter estimation as suggested in this study in section 4..

The preference of the PWM signal provides flexibility for the current input control, its implementation is easy and exhibits great robustness against external disturbances. Furthermore, the PWM signal reduces the energy consumption due to using a discontinuous pulse signal instead of using continuous signal [112].

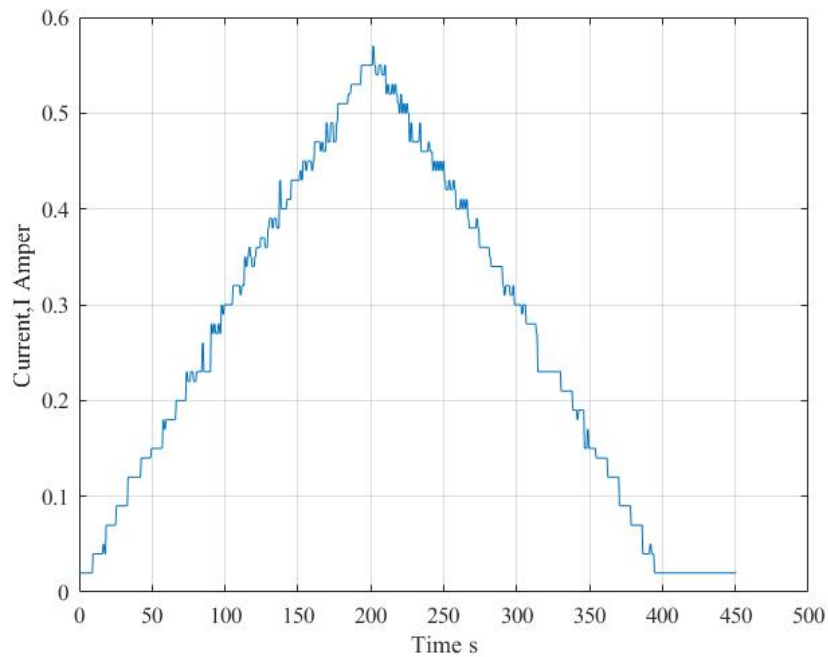


Figure 3.6 Electrical current profile with increasing/decreasing steps

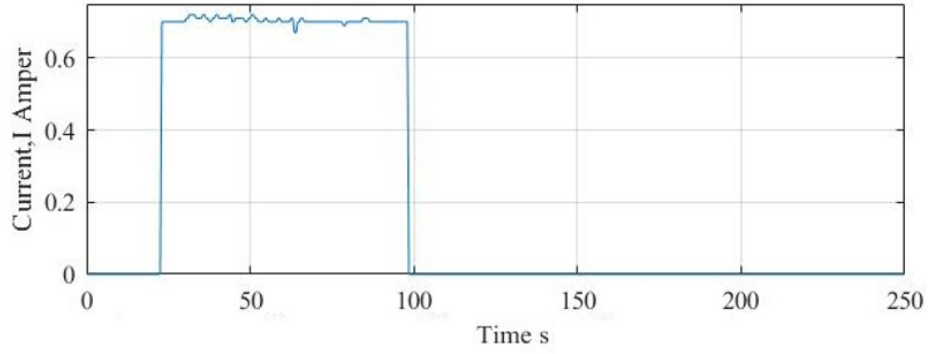


Figure 3.7 Electrical current for fast heating and cooling action ( $T_{\infty}=27.2^{\circ}C$  during the experiment)

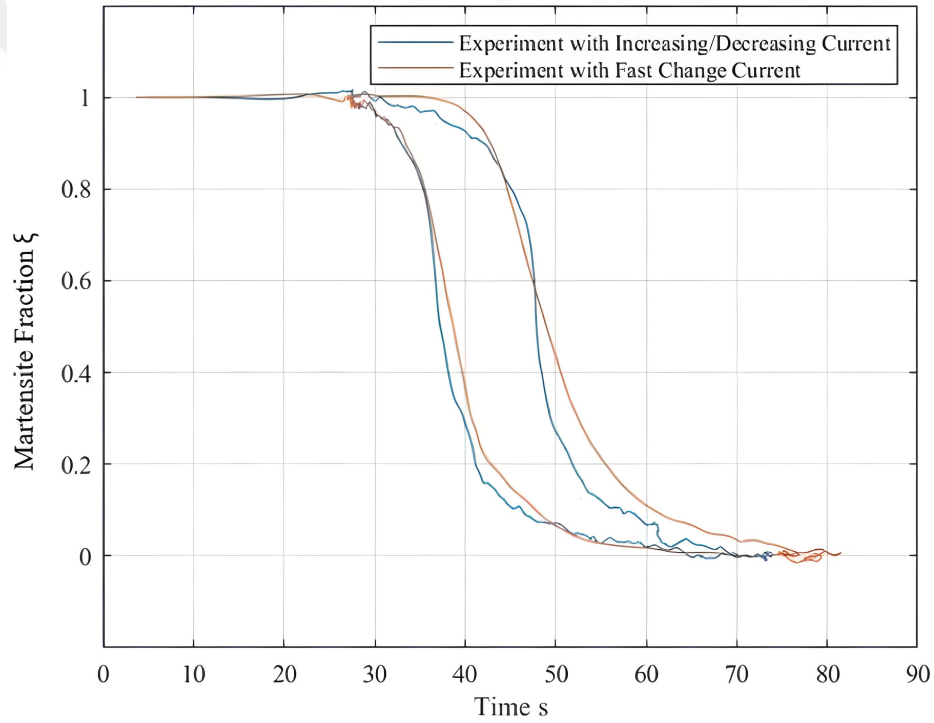


Figure 3.8 Experiment with increasing and decreasing electrical current input in figure 3.6 and change in the hysteresis/in the transformation temperatures during fast heating/cooling action with electrical current input in figure 3.7

### 3.5. Determination of Temperature vs Martensite Fraction Curve and Phase Transformation Temperatures

In this study, measurements of temperature and strain (from distance data measured by the laser sensor) are performed, a reverse transition to phase model from the mechanical model

Table 3.3 Phase transformation temperatures of the SMA wire

| Temperatures    | $^{\circ}\text{C}$ |
|-----------------|--------------------|
| $A_s$           | 40                 |
| $A_f$           | 58                 |
| $M_s$           | 45                 |
| $M_f$           | 32                 |
| at $T_{\infty}$ | 27.2               |

mentioned previously in section 3.3.. The phase transformation temperatures are obtained from the characterization procedure as shown in figure 3.9 and the values are listed in table 3.3. In this study, fast heating/cooling operation is implemented due to some benefits which will be discussed later in section 4.2.2.. The displacement data and the temperature data are collected at 2 Hz sampling rate. The data are merged in Matlab to obtain temperature vs strain curve as given in figure 3.9(a). Furthermore, the data is scaled by the maximum measured strain value, i.e. divide by 5.164, to get the temperature- $\xi$  graph as shown in figure 3.9(b). Here, disturbances during data collection in the experiment are again causing a deviation from the theoretical range between 0 and 1.

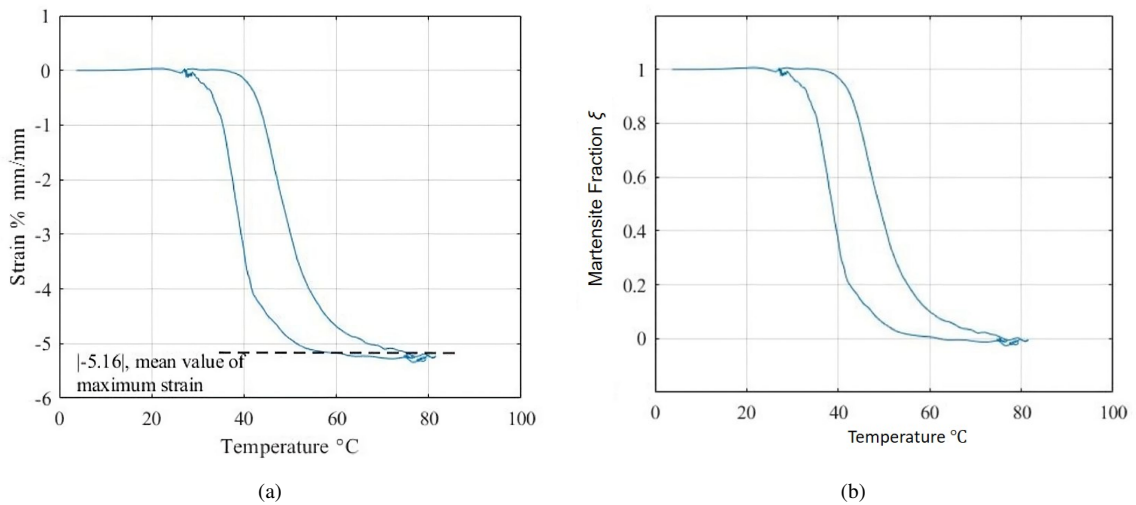


Figure 3.9 Conversion from Temperature-Strain graph in (a) to Temperature- $\xi$  graph in (b)

### 3.6. Ikuta Model Validation

Martensite fraction curves are obtained for heating and cooling parts by putting the temperatures in table 3.3 into equation (2). In figure 3.10, the exponential Ikuta Model provides a decent fitting to the experimental data with some minor inaccuracy in the high temperature region where  $A_f$  and  $M_s$  are active.

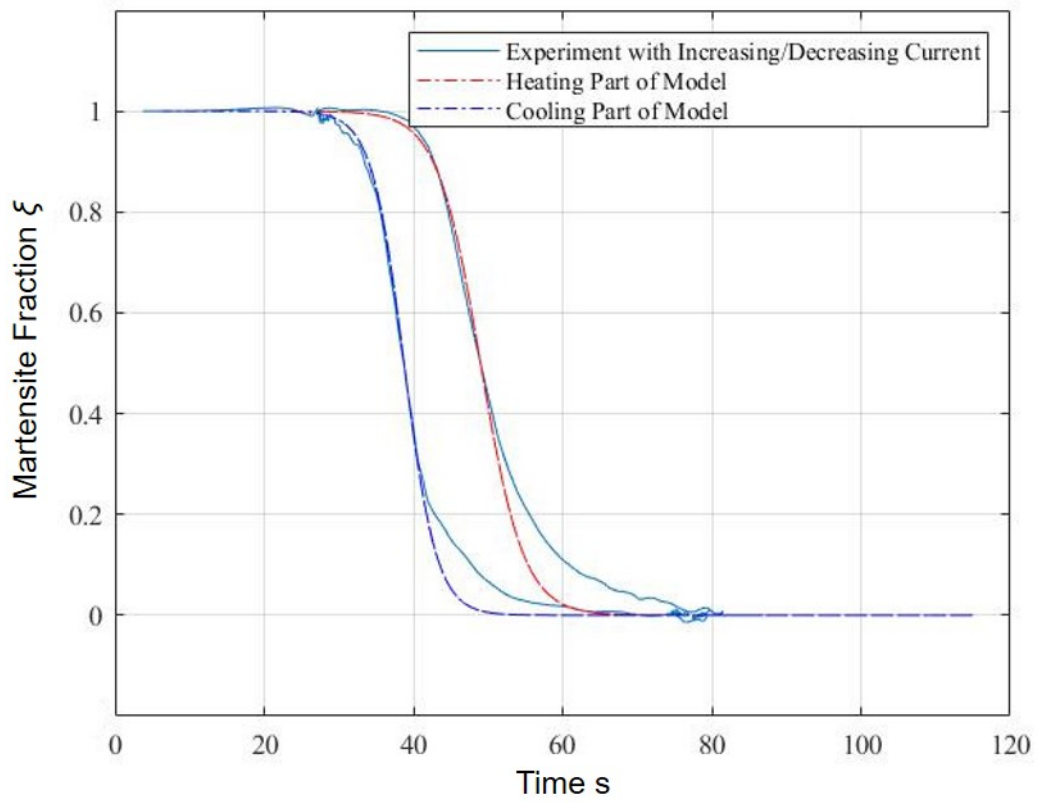


Figure 3.10 Model Validation.

### 3.7. Discussion

Determination of the models for the SMA wire has been discussed in this chapter. After the characterization processes of the wire have been completed, the model used in this study has been validated. By using this background, parameter estimation for the heat transfer model will be discussed.

## 4. MODEL PARAMETER ESTIMATION BY USING RECURSIVE LEAST SQUARE (RLS) METHOD

Previously worded in section 3. as follows: Heat transfer model is the first part of the complete thermomechanical expression of an SMA wire and related to the phase model with the latent heat term. Therefore, heat transfer model parameters are important to improve a complete model. These parameters can not always be given by any manufacturer which the SMA wire is supplied. A method will be suggested to obtain the parameters in section 4..

In this section, Recursive Least Square is considered as a method to obtain the parameters of heat transfer model of the SMA wire. The heat transfer model is validated by the estimated values.

### 4.1. Recursive Least Square (RLS) Method

Recursive least squares (RLS) is an algorithm that tries to find the coefficients of a model to minimize a certain cost function defined by error related to input signal or data. In this Section, basic algorithm is described in [27, 113]. A least square estimation model is given as in equation (8).

$$y(t) = \varphi(t)^T \theta \quad (8)$$

where  $y(t)$  is a measurable quantity or system output,  $\varphi(t)$  is a vector of known quantities or data vector and finally,  $\theta$  is a vector of unknown parameters to be estimated or parameter vector. In statistics, the elements of the vector ,  $\varphi(t)$  are often called regression variables or regressors,  $y(t)$  is called the regressed variable and equation (8) is also known as regression model. Equation (8) can be expressed in more detailed as in equation (9):

$$\begin{aligned}
y(t) &= a_1 y(t-1) + a_2 y(t-2) + \cdots + a_n y(t-n) \\
&= \begin{bmatrix} y(t-1) & y(t-2) & \cdots & y(t-n) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}
\end{aligned} \tag{9}$$

where

$$\theta = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} \tag{10}$$

$$\varphi(t)^T = \begin{bmatrix} y(t-1) & y(t-2) & \cdots & y(t-n) \end{bmatrix} \tag{11}$$

Clearly, it can be seen that it is possible to obtain  $\theta$  vector, i.e. model parameters even though  $y(t)$  takes nonlinear signals. When there are measurements where  $N$  is measurement number, measurement matrix  $\Phi$  and system output vector  $Y$  are derived as equation (12):

$$Y = \Phi \theta \tag{12}$$

where

$$Y^T = \begin{bmatrix} (y(1) & y(2) & \cdots & y(N) \end{bmatrix} \tag{13}$$

$$\varphi(t)^T = \begin{bmatrix} (\varphi(1)^T & \varphi(2)^T \cdots & \varphi(N)^T \end{bmatrix} \tag{14}$$

Assumed that there is an estimation vector  $\hat{\theta}$  of  $\theta$  to predict the output:

$$\hat{y} = \varphi(t)^T \hat{\theta} \quad (15)$$

When defined the error between the actual output and the prediction:

$$\epsilon(t) = y(t) - \hat{y} = y(t) - \varphi(t)^T \hat{\theta} \quad (16)$$

Now, the main purpose is to minimize the error. For this, a cost function is defined like in equation (17):

$$V(\hat{\theta}) = \frac{1}{N} \sum_{t=1}^N \epsilon(t)^2 \quad (17)$$

The aim is to find the parameter estimate  $\hat{\theta}$  such that this cost function is minimum. when noted that the error is given as in equation (18), equation (19) is obtained.

$$\epsilon(t) = Y - \Phi \hat{\theta} \quad (18)$$

$$V(\hat{\theta}) = (Y - \Phi \hat{\theta})^T (Y - \Phi \hat{\theta}) \quad (19)$$

It needs to be found what the  $\hat{\theta}$  vector that makes the cost function minimum is, for this after some derivations in equation (12), equation (20) is governed.

$$\frac{dY}{d\hat{\theta}} = -2((Y - \Phi \hat{\theta})\Phi) = 0(Y - \Phi \hat{\theta})\Phi = 0\hat{\theta} = (\Phi^T \Phi)^{-1} \Phi Y \quad (20)$$

equation (20) can also be written as in equation (21)

$$\hat{\theta} = \left[ \sum_{t=1}^N \varphi(t) \varphi(t)^T \right]^{-1} \left[ \sum_{t=1}^N \varphi(t) y(t) \right] \quad (21)$$

If  $P(t)$  is defined as in equation (22), finally, recursive least square form is obtained after some arrangements. Recursive least square method is given with equation (22)-equation (26) and the algorithm is described under the subtitle RLS Procedure.

$$P(t) = (\Phi^T \Phi)^{-1} \quad (22)$$

$$\hat{\theta}(t) = \hat{\theta}(t-1) - K(t) \epsilon(t) \quad (23)$$

$$\epsilon(t) = y(t) - \varphi(t)^T \hat{\theta}(t-1) \quad (24)$$

$$K(t) = \frac{P(t-1) \varphi}{1 + \varphi(t)^T P(t-1) \varphi(t)} \quad (25)$$

$$P(t) = P(t-1) - K(t) \varphi(t)^T P(t-1) \quad (26)$$

$K(t)$  term makes an effort to suppress the error to provide an equality between the estimation at time  $t$ ,  $\hat{\theta}(t)$  and at the previous time  $\hat{\theta}(t-1)$ . While new data are taking with term  $\varphi^T(t)$ ,  $\hat{\theta}(t-1)$  term correlates the error  $\epsilon(t)$  with previous data.

Recursive Least Squares Estimator block in Simulink/Matlab is used for regression operation. This block has Forgetting Factor term as a default option as given in equation (27) and equation (28). The forgetting factor ( $\lambda$ ) is 1 for a system with constant parameters. The parameters ( $C$ ,  $\Delta h$  and  $h$ ) to be estimated are time invariant as well, therefore the forgetting factor is taken as 1 in this study. Hence, equation (25) and equation (26) are available.

### **RLS Precudure**

*At time step*

1. Formed  $\varphi(t)$  by using the new data
2. Calculated  $\epsilon(t)$  by using equation (18)

3. Calculated  $K(t)$  by using equation (25)
4. Updated  $\hat{\theta}(t - 1)$  to  $\hat{\theta}(t)$  by using equation (23)
5. Updated  $P(t)$  by using equation (26)
6. Waited for the next time step and go back to step 1).

$$K(t) = \frac{P(t-1)\varphi}{\lambda + \varphi(t)^T P(t-1)\varphi(t)} \quad (27)$$

$$P(t) = \frac{1}{\lambda} (P(t-1) - K(t)\varphi(t)^T P(t-1)) \quad (28)$$

## 4.2. RLS Method for The SMA Wire Heat Transfer Model

The determination of SMA wire model is important for an accurate actuator design and its control. The determination of the specific heat and the heat transfer coefficient in the heat transfer model makes it necessary to evaluate some other parameters such as Nusselt number, Reynolds number or Prandtl number [12, 102]. Estimated values obtained from different models are compared with the theoretical ones in [102] for the convection coefficient determination. The estimation errors show that the models for thin vertical cylinders are not convenient for the accurate determination of the heat transfer coefficient of an SMA actuator. Therefore, the adaptable estimation of the heat transfer coefficient in the changing environmental circumstances becomes important. In another research study, the mean values of model parameters are obtained empirically by carrying out some recursive experiments [10]. While this approach allows for lower order parameter identification by ignoring unmodeled effects such as radiation and conduction, it introduces a lot of repetitive experimentations. [114, 115] also offers experimental procedures to identify the model parameters. The convection has a major effect and is presented as a parameter for the design of the actuator compared with other heat transfer mechanisms, i.e radiation and conduction [116]. Likewise, it is showed that the convection coefficient is different for heating and cooling whereas common practice does not pay attention to the cooling or heating cycle [117]. Furthermore, there are also other shortcomings in phenomenological models for SMA

characteristics under force change [118, 119]. The deficiencies in the modelling become significant while SMA wires are used as actuator. As a result, quick estimation of the model parameters to be used in the heat transfer model gets important for accurate and repeatable actuation.

In this study, parameters for the heat transfer model are estimated using a single set of experimental data by means of the Recursive Least Square (RLS) Method. The method is shown to give the most appropriate values in approximating the model to the actual measurement. The heat transfer model is the first step of creating a mechanical model and the mechanical model is necessary when the wire is integrated into any other actuation systems. The literature proposes sub-mathematical equations and these equations may lead to detailed some other parameters [12, 102]. Besides, the parameters describing full model of actuation system are estimated. These parameters have no physical meaning such as specific heat or latent heat coefficients. Here, a practical in situ estimation method is proposed where the estimated parameters can be updated simply and fast with a less data requirement. Thus, proposed method may provide the implication of the adaptive method on the SMA actuation controllers.

#### **4.2.1. Regression Form of The Heat Transfer Model**

The heat transfer model in equation (1) must be rearranged to estimate unknown parameters by RLS algorithm. The final regression form is given in equation (29). Here, the system output,  $y(t)$ , is constituted by the electrical power for a constant electrical resistance and measured electrical current. Moreover, using the known or measured quantities, i.e. temperature, derivative of the temperature obtained from the temperature data by using Simulink derivative block and derivative of martensite fraction, are collected into the data vector,  $\varphi(t)$ . Finally, the unknown parameters to be estimated are grouped into the parameter vector,  $\theta$ . Defining  $\delta(t) = T(t) - T_{\infty}$ , one may write  $\dot{\delta}(t) = \dot{T}(t)$ , because  $T_{\infty}$  is constant.

$$I^2 R = \begin{bmatrix} \dot{\delta} & \dot{\xi} & \dot{\delta} \end{bmatrix} \begin{bmatrix} C\rho V \\ \Delta h\rho V \\ hA \end{bmatrix} \quad (29)$$

#### 4.2.2. Set of The Data for RLS Estimation

The electrical resistance of a SMA wire is known to be reduced with an increase the wire temperature. Furthermore, the relation between the electrical resistance and strain is hysteric similar to the relation between temperature and strain in heating and cooling processes. Electrical resistance variation in the wire results an increase of the electrical current in the wire or voltage drop [87, 99]. Therefore, undesired peaks and drops in the electrical current can be seen in figure 4.1, especially at the transition from martensite to the austenite phase and high temperatures over 0.2 A electrical current. It is clear that the parameter estimation during the heating seems not accurate, because the resistance is taken as constant in this study. However, after heating over  $A_s$  and cutting off the electrical current, electrical power term in equation 1 drops and the estimation of the constant parameters become easier. Hence, estimation procedure is carried out in the fast heating/cooling case as shown in figure 4.2. Furthermore, while long time period is better for the characterization, it is shown that making estimation with just a sampling frequency of 2 S/s (sample/second) and in shorter times is possible.

### 4.3. Results

RLS method gives the estimated values of all of the integrated terms in parameter vector:  $C\rho V$ ,  $\Delta h\rho V$ ,  $hA$ .  $C$ ,  $\rho$  and  $V$  are constant and after estimation, unknown parameters of the heat transfer model,  $C$ ,  $\Delta h$  and  $h$ , can be determined. To be able to make an estimation of the unknown parameters, firstly, the electrical power in the output vector has been measured. Electrical current  $I$  has been recorded with a high current H bridge module (IBT-2). Electrical resistance  $R$ , has been measured for the wire piece of length of 108

mm by a multimeter and measured as a constant of  $1.34 \, \Omega$  at the room temperature (i.e., martensite finish temperature for the wire in this study). Furthermore, the temperature has been measured with a thermocouple and the change of the temperature is derived for the data vector. Another term,  $\dot{\xi}$  in data vector, can be obtained by two different method. First method is to use the phase model depending on the temperature and the second one is to use directly the laser sensor data.

#### 4.3.1. Estimation with Phase Model

The temperature is only measured in this study. Then, the time rate of change of the temperature is reached by using the derivative of the temperature data. The phase model depending on the temperature in equation (2) is used to obtain the derivation of  $\dot{\xi}$  term

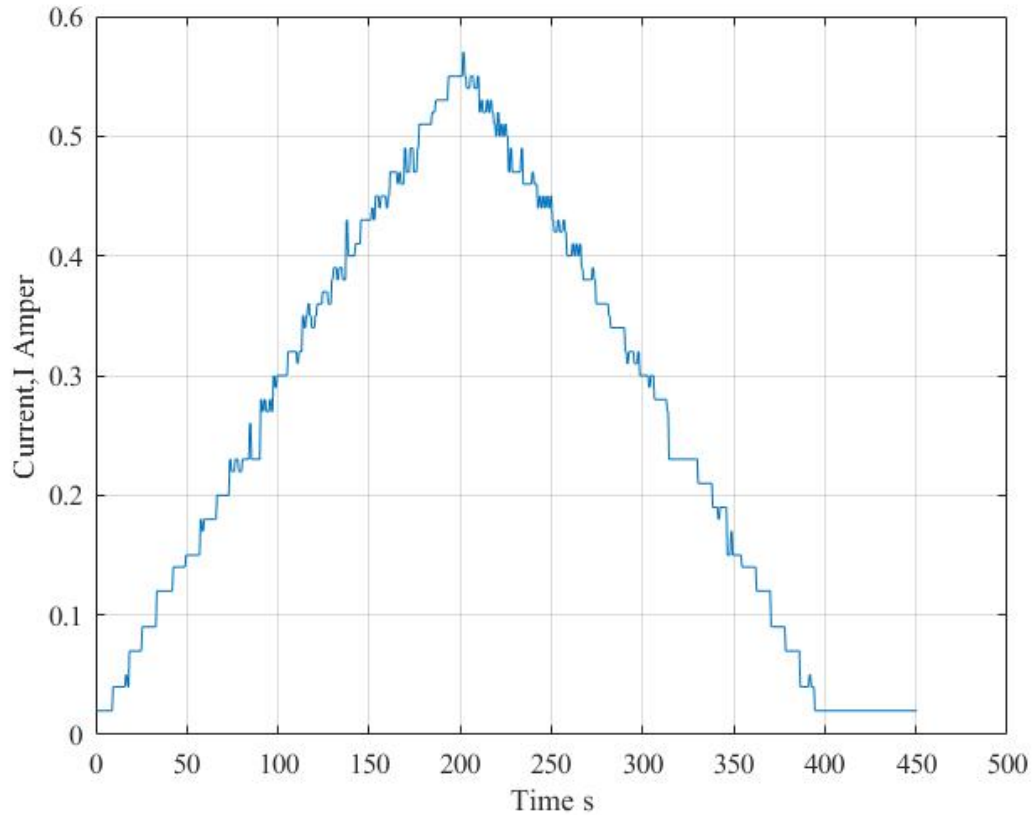


Figure 4.1 Electrical current profile with increasing/decreasing steps

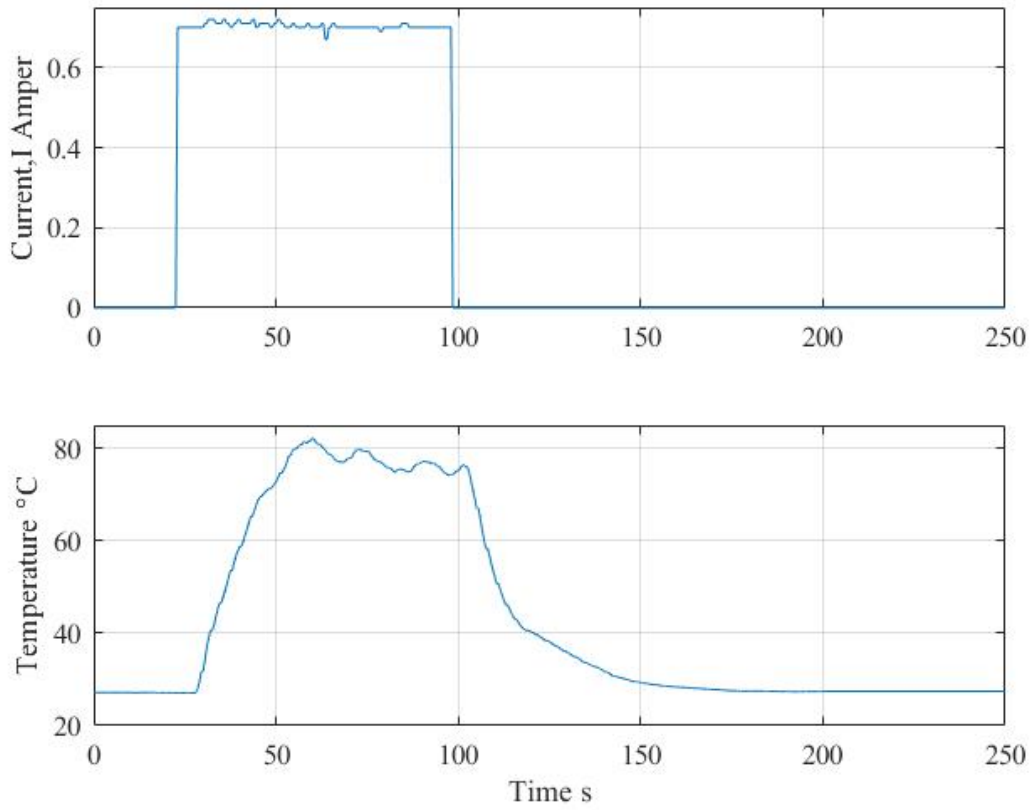


Figure 4.2 Fast heating and cooling action ( $T_{\infty}=27.2^{\circ}C$  during the experiment)

from the temperature data. Whole estimation procedure is given in figure 4.3. Estimated parameters and errors are given in figure 4.4 which are the output of the Recursive Least Squares Estimator block in Simulink/Matlab. The major peak of the estimation around 25th second coincides with the onset of the current given into the wire. Furthermore, the convergent parts of the estimations are zoomed in and the converged values as “Estimated Values with RSL method” are listed in table 4.1.

#### 4.3.2. Estimation with Laser Sensor Data

Here, estimation with the laser sensor data is done to observe whether using the laser sensor data ensures more accurate estimation comparing with the model data. Whole procedure is given in figure 4.5. Firstly, an arrangement using the laser sensor data is completed to reach

the  $\xi$  as revealed in Section "Determination of temperature- $\xi$  curve and phase transformation temperatures". Then,  $\xi$  is added by taking the derivative to the RLS algorithm. As output of the Recursive Least Squares Estimator block in Simulink/Matlab, estimated parameters and estimation error are graphically given in figure 4.6. The major peak of the estimation around 25th second coincides with the beginning of the current given into the wire. Also, the convergent parts of the estimations are zoomed in and the converged values as estimated values are listed in table 4.1.



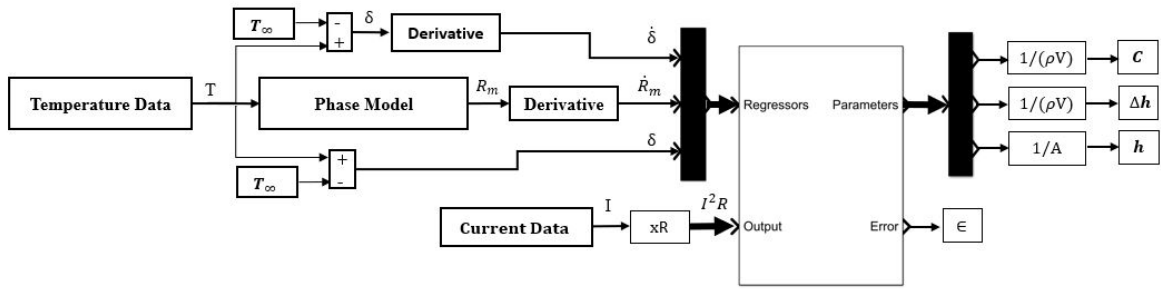


Figure 4.3 "Phase model" based RLS estimation diagram

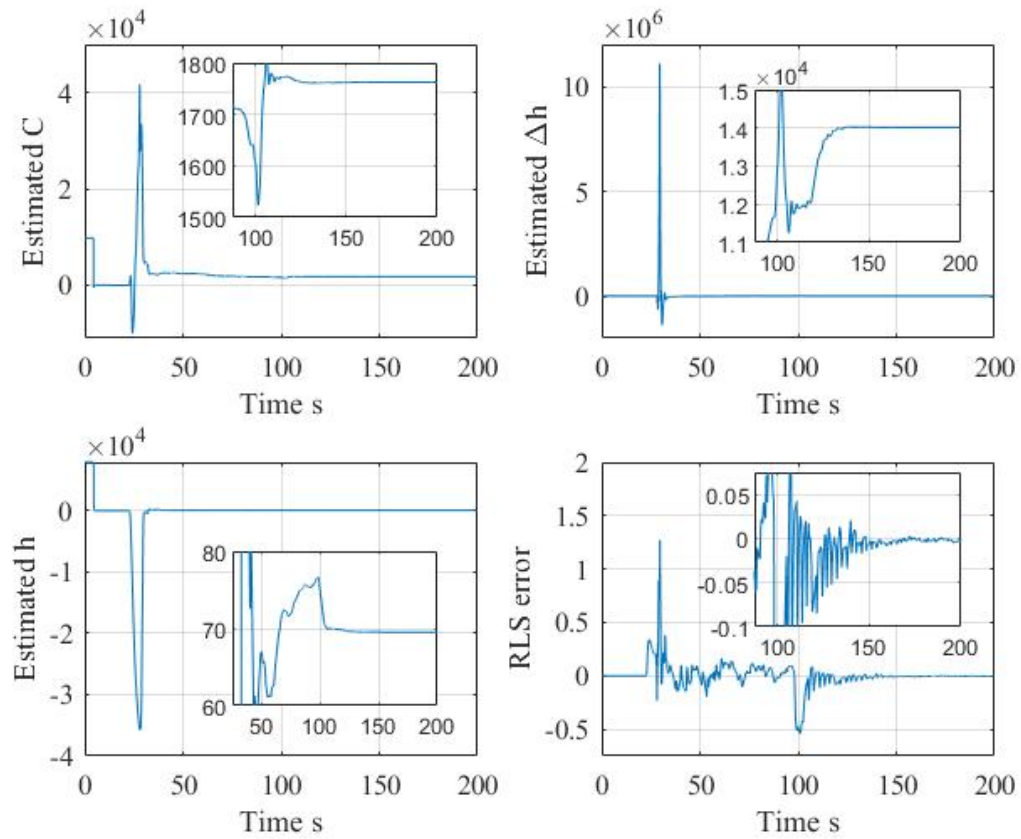


Figure 4.4 Estimated parameters: specific heat coefficient  $C$  [J/(kg°C)], latent heat coefficient  $\Delta h$  [J/kg], heat transfer coefficient  $h$  [W/(m<sup>2</sup>K)] and estimation error, based on phase model

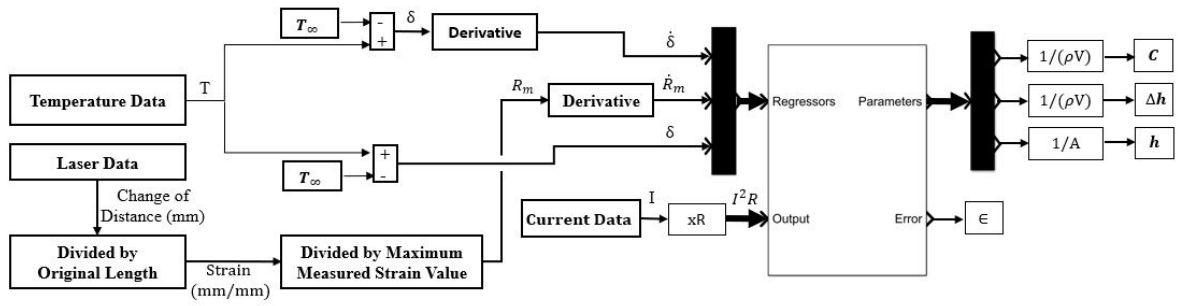


Figure 4.5 "Laser sensor data" based RLS estimation diagram

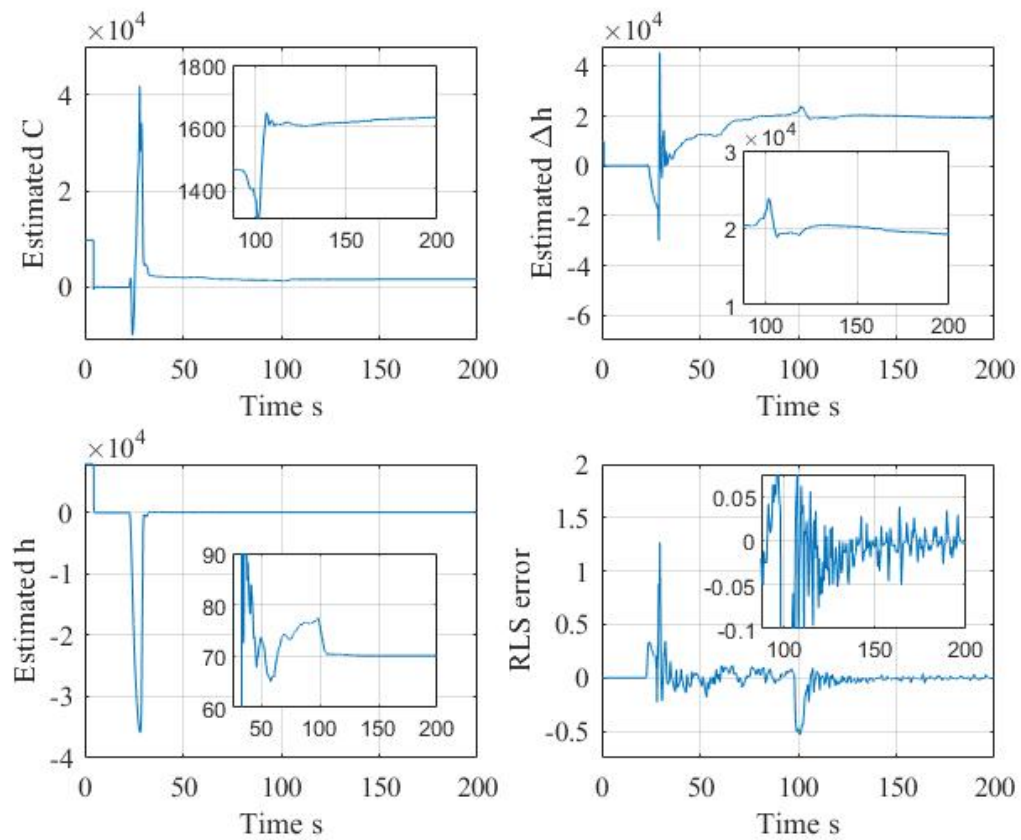


Figure 4.6 Estimated parameters: specific heat coefficient  $C$  [J/(kg°C)], latent heat coefficient  $\Delta h$  [J/kg], heat transfer coefficient  $h$  [W/(m<sup>2</sup>K)] and estimation error, based on laser sensor data

Table 4.1 Heat transfer model parameters of the SMA wire

| Parameters | Units                | Estimated Values with RLS Method |             |
|------------|----------------------|----------------------------------|-------------|
|            |                      | Model Based                      | Laser Based |
| C          | J/(kg°C)             | 1750                             | 1630        |
| $\Delta h$ | kJ/kg                | 14                               | 20          |
| h          | W/(m <sup>2</sup> K) | 70                               | 70          |

#### 4.4. Discussion

A sample graph is given in figure 4.2 for the fast heating and cooling action of the SMA wire. In this specific experiment, a square shape electrical current is fed to the SMA wire. Accordingly, the SMA wire response to this sudden excitation with fast heating and cooling cycle. Some fluctuations in the electrical current are observed due to the change of the

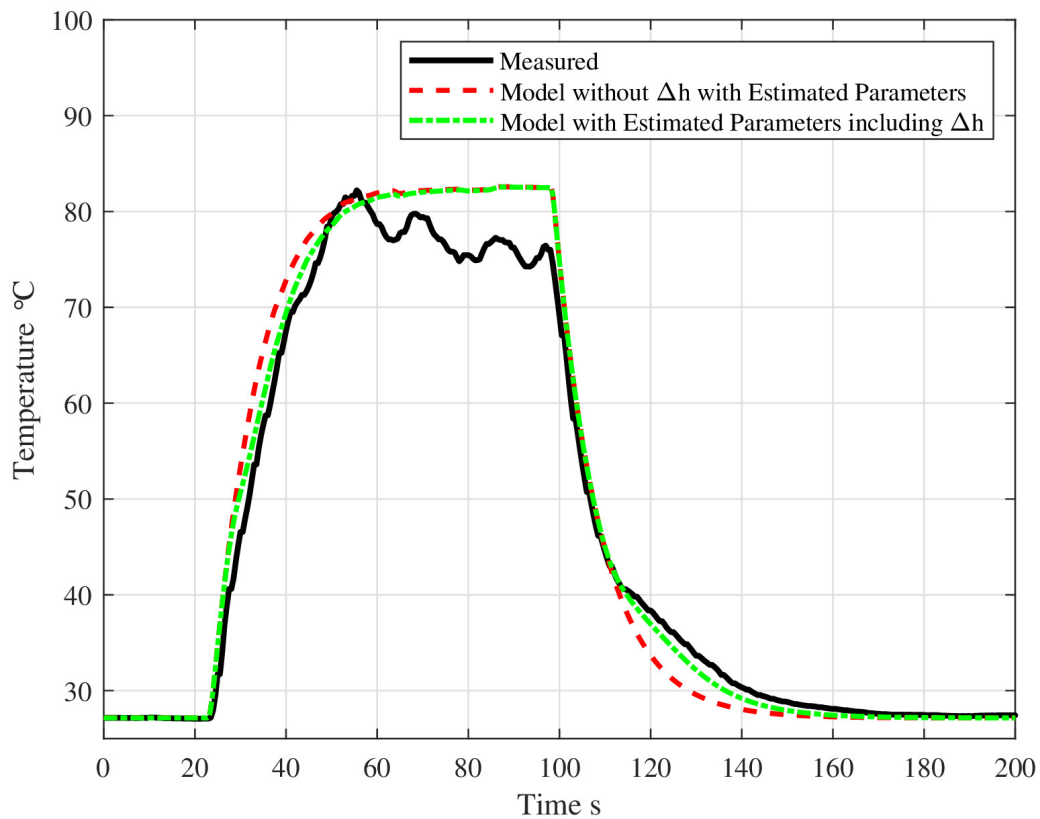


Figure 4.7 Temperatures based on phase model

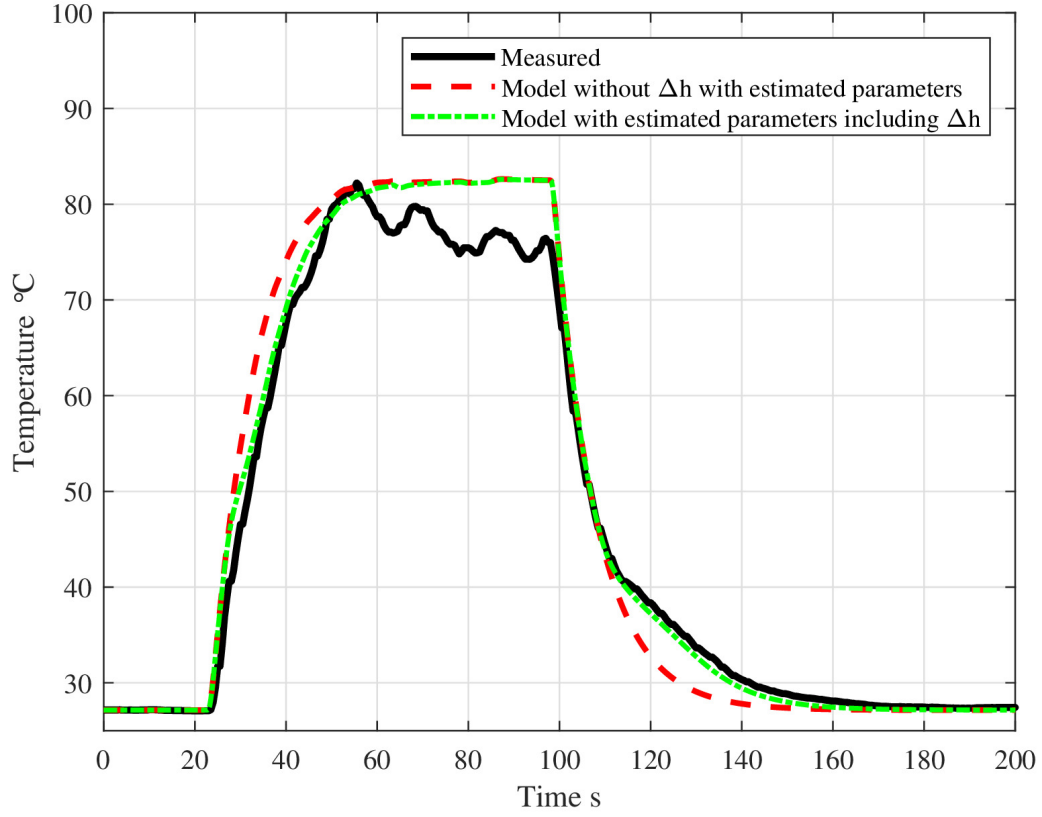


Figure 4.8 Temperatures based on laser sensor data

electrical resistance with the temperature. The electrical current is cut-off near to the 100th second where cooling by natural convection controls the temperature until approximately 175th second. The cooling period shows fast drop for the wire temperature until  $M_s=45^\circ\text{C}$ , then the slope becomes a little flatter, where  $\Delta h$  parameter becomes effective, because of the phase transformation from austenite to martensite. Furthermore, electrical power term  $I^2R$  drops in this period of the time and negative effect of the change of the electrical resistance for the parameter estimation are prevented. Hence, this is the most suitable time period for an accurate parameter estimation.

$$RE_i = \frac{\|T_{model,i} - T_{measured}\|_2}{\|T_{measured}\|_2} \quad (30)$$

where  $i=1$  and  $2$ .

The parameters estimated using RLS overlaps the measured temperature. The contribution of adding latent heat term into the model and at what degree using the parameters coming from RLS enhances the model is investigated. Norm error analysis is performed using equation 30. RE stands for relative norm error. The results are listed in table 4.2.

| PHASE MODEL | $C, \Delta h$ and $h$ are estimated                                                      | Relative Norm Error $RE_i$ |
|-------------|------------------------------------------------------------------------------------------|----------------------------|
| i=          | vs                                                                                       | Measured Temperature       |
| 1           | Parameters from RLS estimation and without latent energy term in the heat transfer model | 0.0679                     |
| 2           | Parameters from RLS estimation and with latent energy term in the heat transfer model    | 0.0541                     |
| LASER DATA  | $C, \Delta h$ and $h$ are estimated                                                      | Relative Norm Error $RE_i$ |
| i=          | vs                                                                                       | Measured Temperature       |
| 1           | Parameters from RLS estimation and without latent energy term in the heat transfer model | 0.0746                     |
| 2           | Parameters from RLS estimation and with latent energy term in the heat transfer model    | 0.0535                     |

Table 4.2 Norm errors

The model fittings by using the estimated parameters and the measurement are shown in figure 4.7 and figure 4.8 along with the measurement results for the temperatures based on phase model and the temperatures based on laser sensor data, respectively. Here, the natural convection is the most important part of the model since it is effective on the entire process. Likewise, the heat convection coefficient,  $h$ , is the parameter having major effect on the system. This is due to the fact that  $h$  multiplies  $T$  not the change of the temperature  $T$ . Thus, it is observed that estimation of the  $h$  is the same with a numerical value of  $70 \text{ W}/(m^2\text{K})$  and quite stiff for both “phase model” and “laser data” procedures. In general meaning,

although phase model and laser data based estimation give different results for  $C$  and  $\Delta h$ , these differences are not as apparent as the effect of  $h$ , because  $h$  dominates overlapping between the measured temperature and the model. In a more accurate approach, adding  $\Delta h$  results in a better model for both the phase model and laser data procedures, as it can be observed especially in the cooling time period of figure 4.7 and figure 4.8. Also, considering error values in table 4.2, the effect of adding  $\Delta h$  can be seen. According to this, norm error is reduced from 0.0679 to 0.0541, i.e. enhanced at 20% percent, for phase model based estimation procedure and norm error is reduced from 0.0746 to 0.0535, i.e. enhanced at 28% percent, for laser data based estimation procedure as well. If remembered that the difference between model and measured values especially at  $M_s$  and  $A_f$  in figure 3.10, it is expected that the estimation procedure with laser data will give better estimation result especially for  $\Delta h$ . Comparing figure 4.8 with figure 4.7, it can be seen, especially between 110 and 140th seconds, that the estimated value  $\Delta h=20$  kJ/kg resulting from laser data is better estimation for the model but this is not major: considering the norm errors are 0.0541 for phase model based procedure and 0.0535 for laser data based procedure, laser data based procedure in estimation provides enhancement with just 1% percent.

There are some other advantages of using the laser data for the estimation as well. 3.10 demonstrates that the accuracy of the model reduces at  $A_f$  and  $M_s$  whereas the laser data usage in the model prevents this situation for the estimation. Secondly, if the loading or the rate of change of the temperature with the input current level varies, phase transformation temperatures must be updated to obtain  $\xi$  from the phase model. It means that SMA characterization is needed for every new loading or in the rate of change of the temperature. However, a new characterization procedure is not needed if the estimation is performed by using laser data.

As already mentioned, the SMA wire has wide application fields in engineering especially as an actuator. There are many different environmental conditions that these actuators would stay in operation. As an example, ambient temperature might be variable or SMA wire is externally chilled for a fast response demand. In these two cases, the most dominant parameter in the heat transfer model would be the  $h$  and it depends on the

Table 4.3 Dimensional and material properties of the SMA wire

| $D(mm)$ | $L(mm)$ | $R(\Omega)$ | $\rho(kg/m^3)$ |
|---------|---------|-------------|----------------|
| 1       | 95      | 1           | 6450           |

ambient temperature. Furthermore, manufacturer of the SMA's may have not determined specifications of the SMA material, which is also effective for this study. Therefore, heat transfer model parameters must be updated in these cases. Dedicated experiments may lead to the system identification with heat transfer model parameters whereas it leads to storage of large data which needs to be processed and does not work in real time. However, RLS estimation method produces good estimations for the unknown parameters. This method is very practical for real time, hardware in the loop tests, actuator designs.

In this study,  $C$ ,  $\Delta h$  and  $h$  parameters are calculated using the constants of  $V$ ,  $A$  and  $\rho$ . However, one does not need to know these values separately to reach the temperature from the heat transfer model. In the first step, the output of the regression block estimates parameters all together:  $C\rho V$ ,  $\Delta h$ ,  $\rho V$  and  $hA$  as it is seen in figure 4.3 and figure 4.4. Even if these terms are remained in this way, it is possible to obtain the temperature  $T$  from the model. Therefore, it can be inferred that it is not needed to know  $\rho$  as materials property and also,  $V$  and  $A$  as dimensional properties.

While considering the subject of overlapping between measured temperature and the models, a detail that may also be affected on measuring is needed to mention: the wire surface is very narrow to make the measuring end of thermocouple touch the surface. This is a kind of source for error and explains that fewer temperature values can be measured especially at high temperatures.

#### 4.5. RLS Procedure for Another Wire

In this section, it is desired to validate the RLS method by applying it on another wire having different properties. Its dimensional properties are given in table 4.3.

Table 4.4 Phase transition and ambient temperatures

| $A_s$ | $A_f$ | $M_s$ | $M_f$ | $T_\infty$ |
|-------|-------|-------|-------|------------|
| 48    | 57    | 43    | 31    | 26.6       |

#### 4.5.1. Characterization of The SMA Wire

By using the same procedure with the previously interested wire, characterization of the wire is carried out by fast heating/cooling method under the electrical current and with temperature measured by thermocouple seen in figure 4.9. The distance has been recorded by laser distance sensor. After the transition to the strain with these data in figure 4.10 and eventually, martensite fraction curve in figure 4.11 are obtained by using maximum strain value. The phase transition temperatures are given in table 4.4 for this wire. Ikuta phase model validation by using these temperatures can also be seen in figure 4.12.

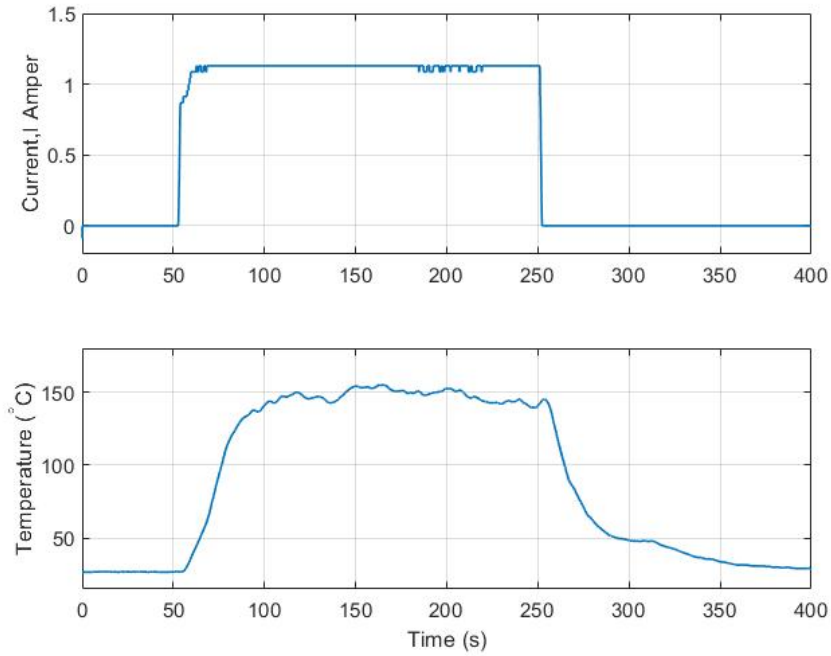


Figure 4.9 Fast heating and cooling action ( $T_\infty = 26.6^\circ\text{C}$  during the experiment).

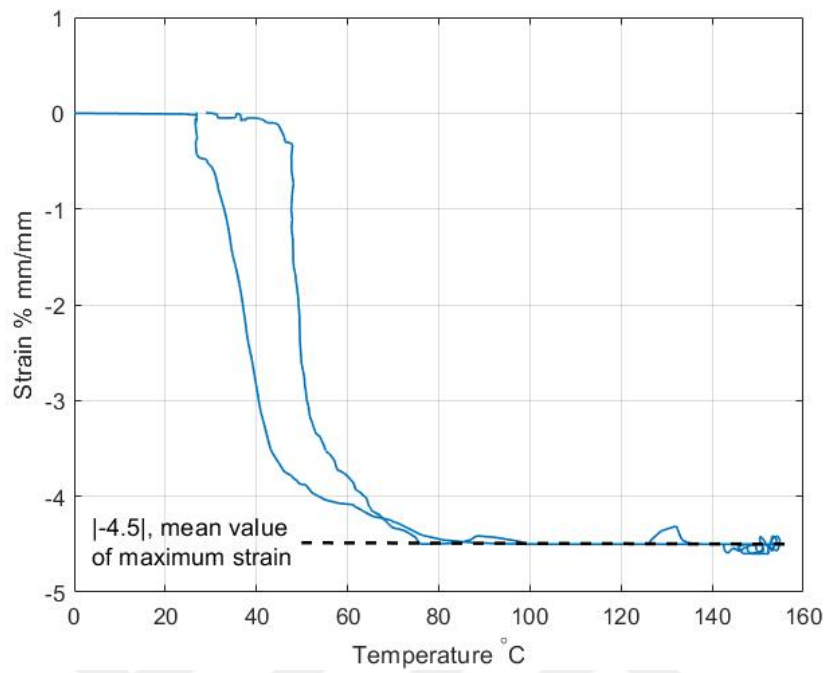


Figure 4.10 Temperature-Strain graph

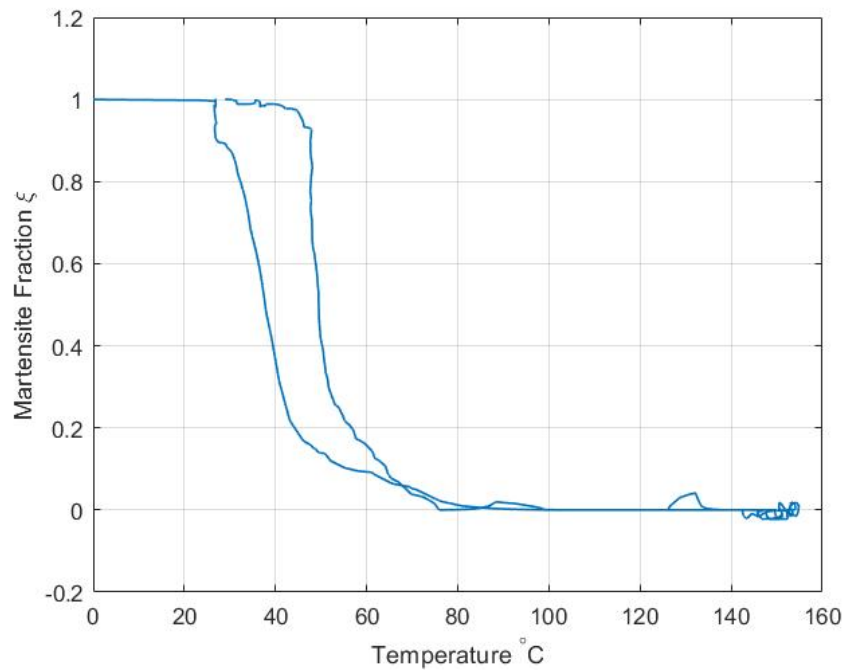


Figure 4.11 Conversion from figure 4.10 to Temperature- $\xi$  graph

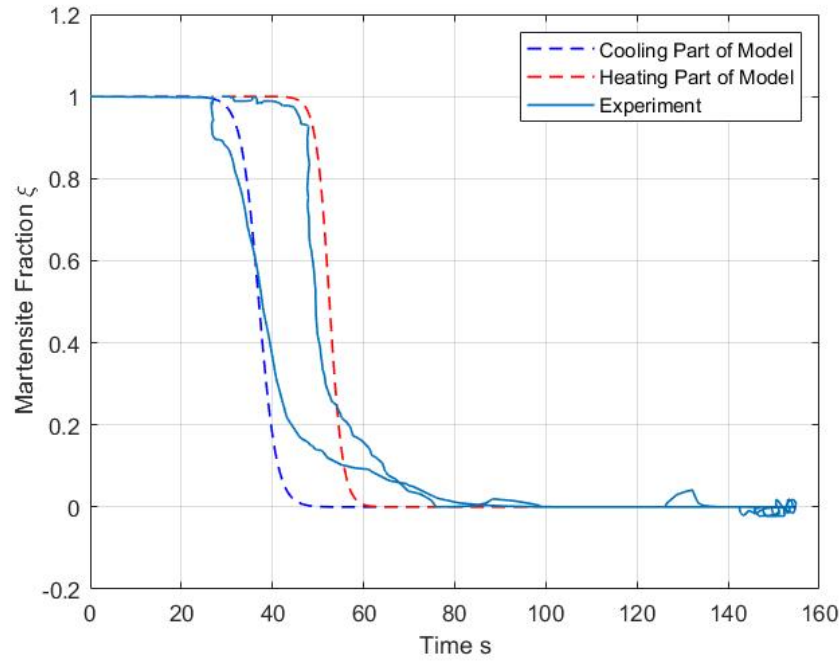


Figure 4.12 Model validation

#### 4.5.2. RLS Parameter Estimation and Validation

It is understood that the convergence of the parameter's values in figure 4.13, which are tabulated in table 4.5, indicates the validity of the approach. It is shown that the temperature estimate resulting from the heat transfer model derived from the estimated parameters matches with the measured temperature data as it can be seen in figure 4.14. Also, it is shown that the accuracy of the model can be enhanced 35% by the addition of the latent heat term according to figure 4.14.

Table 4.5 Heat transfer model parameters of the SMA wire

|                                  | $C(J/(kg^{\circ}C))$ | $\Delta h(kJ/kg)$ | $h(W/(m^2K))$ |
|----------------------------------|----------------------|-------------------|---------------|
| Estimated Values with RLS Method | 3000                 | 155               | 41            |

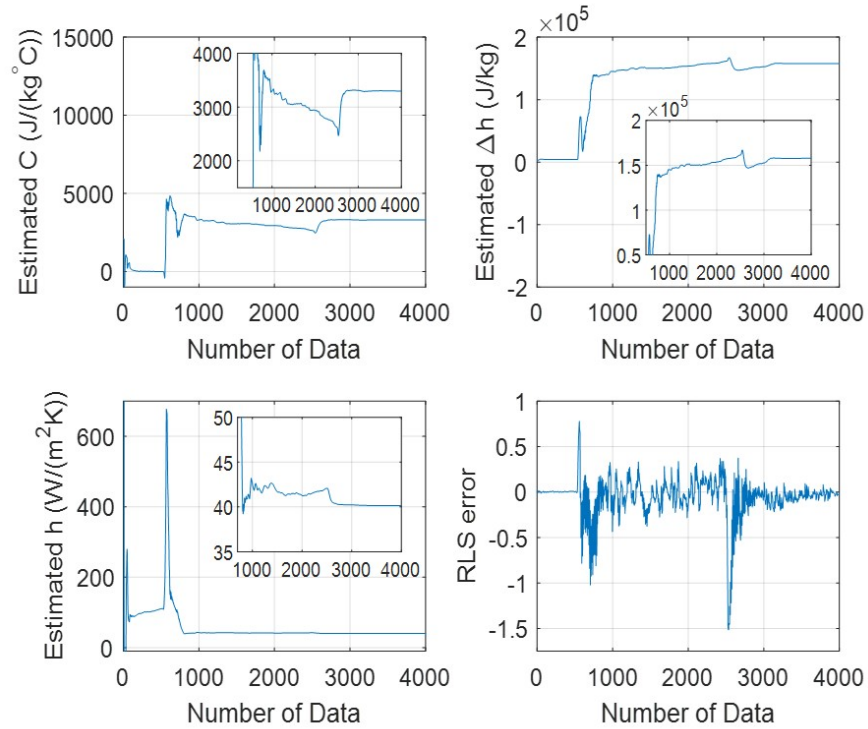


Figure 4.13 Estimated parameters: specific heat coefficient  $C$  [ $\text{J}/(\text{kg}^\circ\text{C})$ ], latent heat coefficient  $\Delta h$  [ $\text{J}/\text{kg}$ ], heat transfer coefficient  $h$  [ $\text{W}/(\text{m}^2\text{K})$ ] and estimation error

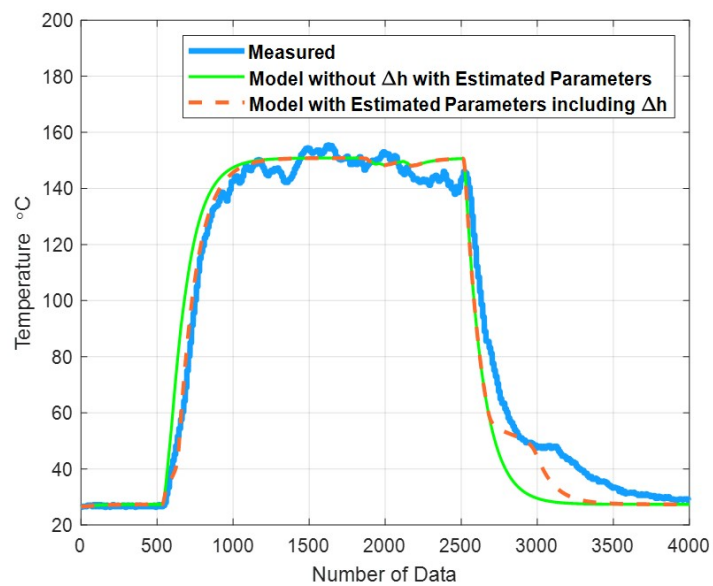


Figure 4.14 Temperatures

## 4.6. Discussion

In this chapter, firstly, the background about RLS method has been briefly mentioned. The method has been applied for the heat transfer model. The model with estimated parameters has given suitable results with the measured. In conclusion, it is shown by testing with two different SMA wires that RLS method works.



## 5. CONTROL OF THE SMA WIRE

In this section, strain control of an SMA wire is discussed. The SMA wire used is different from the one used in RLS section with regards to activation temperature given by the supplier, Nexmetal, in spite of the same dimensional and material properties (in table 3.2). Thus, determination of the hysteresis curve is seen necessary. The curve is given in figure 5.1 and according to the curve, phase transition temperatures to use in the next sections for the phase model are listed in table 5.1.

3 kg weight has been hung at the free end of the wire while obtaining the curve and elongation of near 3.5 mm has been seen. The control operation is carried out in this limit under the same loading. Here, it must be emphasized that % strain is the same value with the changing distance because the length of the wire 100 mm. Therefore, as an example, desired reference signal of 0.5 mm means 0.5% strain in the same time.

Firstly, in section 5.2., in complete strain region of the SMA wire, controller gains are tuned so as to exhibit the best performance.

In section 5.3., reference signals are limited to three specific ranges where are largely martensite, phase transition and largely austenite, respectively to observe control performance. Also, the experiments in the same regions are repeated for increasing frequencies if the reference input is the sine signal. Thus, it is desired to observe whether the wire having heating-cooling cycle can be controlled by the same controller gains or not. Moreover, SMA model responses obtained by using results coming from RLS estimation are added to each experimental result.

The experimental data are filtered by a Butterworth filter in Matlab. The filter is designed optimal as so not to lose the measurement. Vibrations on the data in all figures related to the reference tracking are due to turning on/off current during the control and oscillations on the reflective surface that the laser hits during distance measurement. The reflective surface also vibrates because of the freedom between the SMA wire and the rope the dead weight hung at its end and the contact between the rope and pulley.

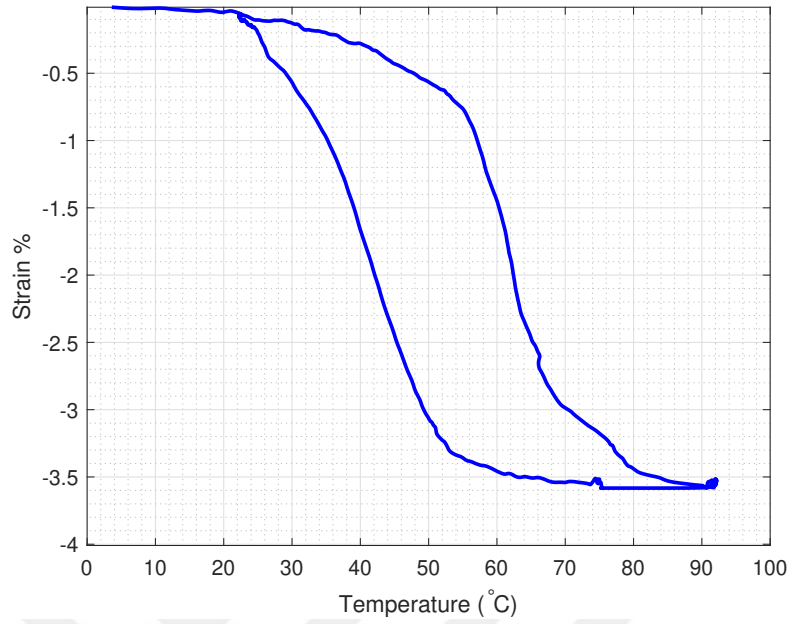


Figure 5.1 SMA hysteresis curve under 150 MPa load

The control diagrams for both model and actual system (SMA wire) are given in figure 5.2 and 5.3. Actual duty cycles in the experiments in figure 5.3 are saturated by 40% (or 1.2 A electrical current) to avoid possible damage in the wire under high currents, although the electronic circuit has been designed to produce high current until 3 A.

## 5.1. PWM Duty Cycle and Corresponding Current

The electronic circuit works based on PWM signal. In other words, it takes a % duty cycle command from the PC and gives the corresponding current into the wire. The electronic circuit is also designed to measure the current passing through the wire. Hence, a relation is reached between % duty cycle and measured current. The measured current data under

Table 5.1 Phase transformation temperatures of the SMA wire

| Temperatures | °C |
|--------------|----|
| $A_s$        | 56 |
| $A_f$        | 73 |
| $M_s$        | 53 |
| $M_f$        | 32 |

constant % duty cycles are marked in figure 5.4 to obtain the calibration line. As can be seen, the electronic circuit does not produce current until %20 duty cycle. The current raises with 0.064 A on the average in next each % duty cycle increase.

## **5.2. Controller Gains Tuning and Control Action in The Complete Strain Range**

The experiment and the model simulation in Simulink are carried out together to find the optimal controller gains. Firstly, the controller gains are easily tuned in the simulation in Simulink and then, tested in the experiment. Thus, PI has been seen as the optimal controller and gains are  $K_P=0.4$  and  $K_I=0.1$ , respectively. Tracking performances for a triangular and sine strain reference inputs are given in figure 5.5 and figure 5.7 and control inputs are given in figure 5.6 and figure 5.8.

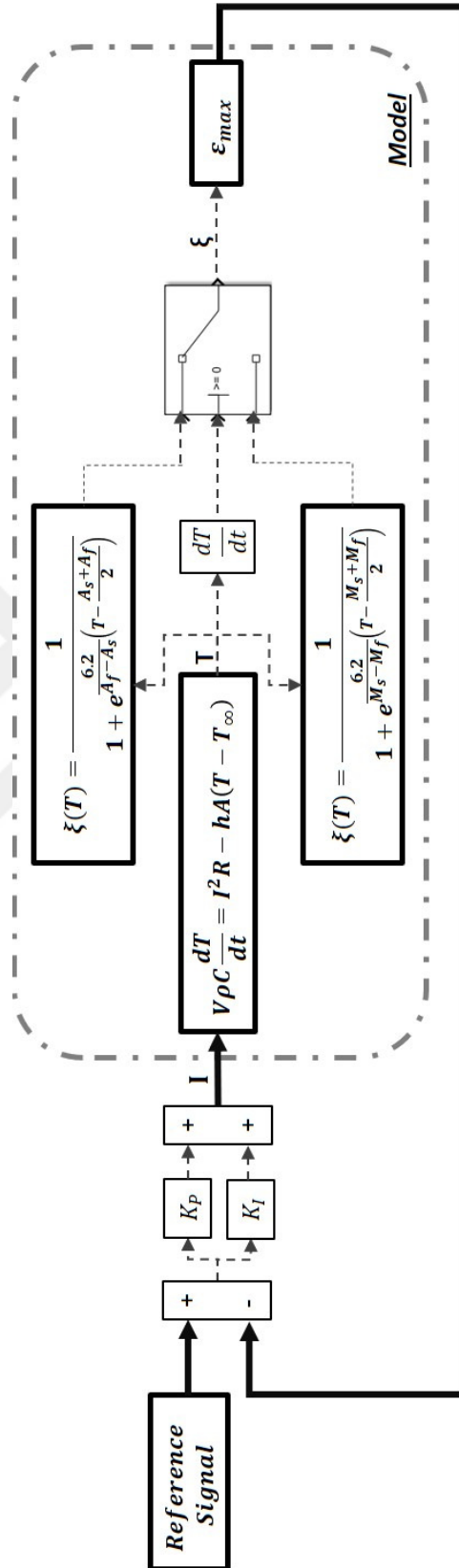


Figure 5.2 Control diagram for the model

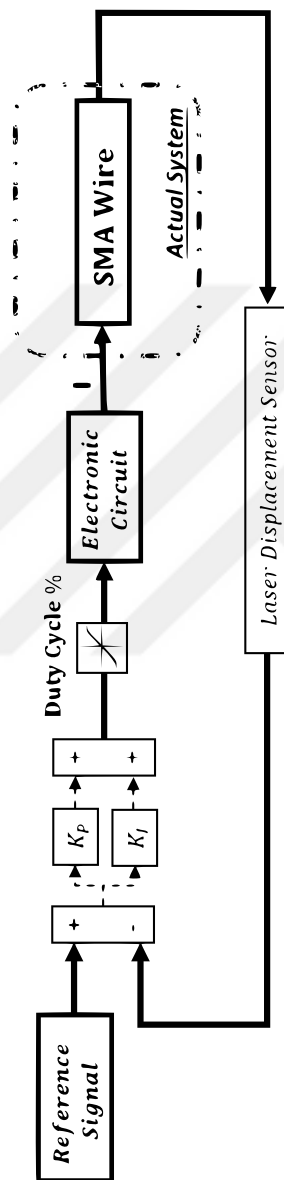


Figure 5.3 Control diagram for the actual system

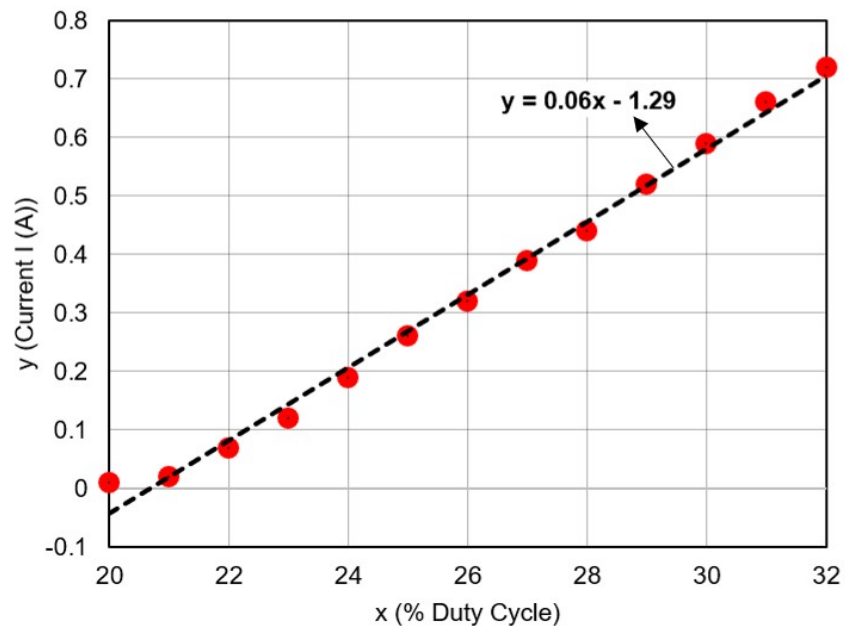


Figure 5.4 Duty cycle vs electrical current

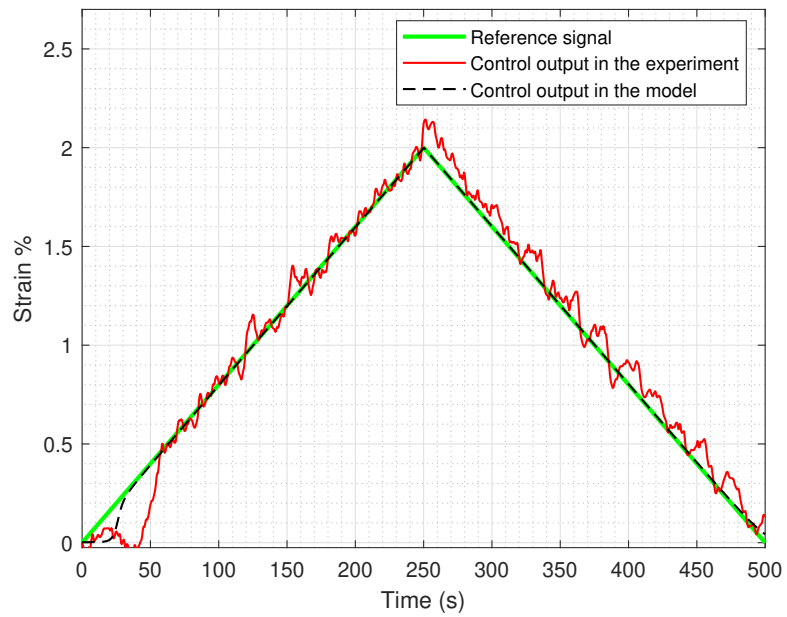
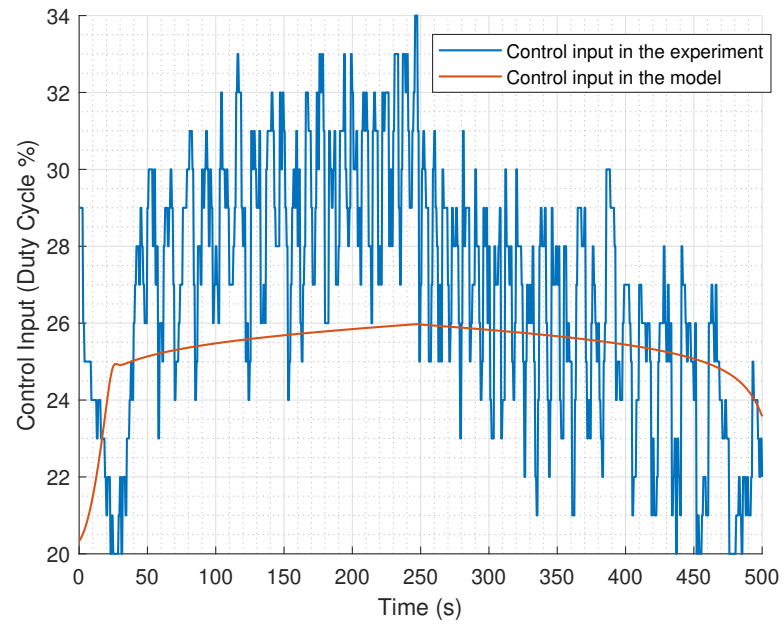
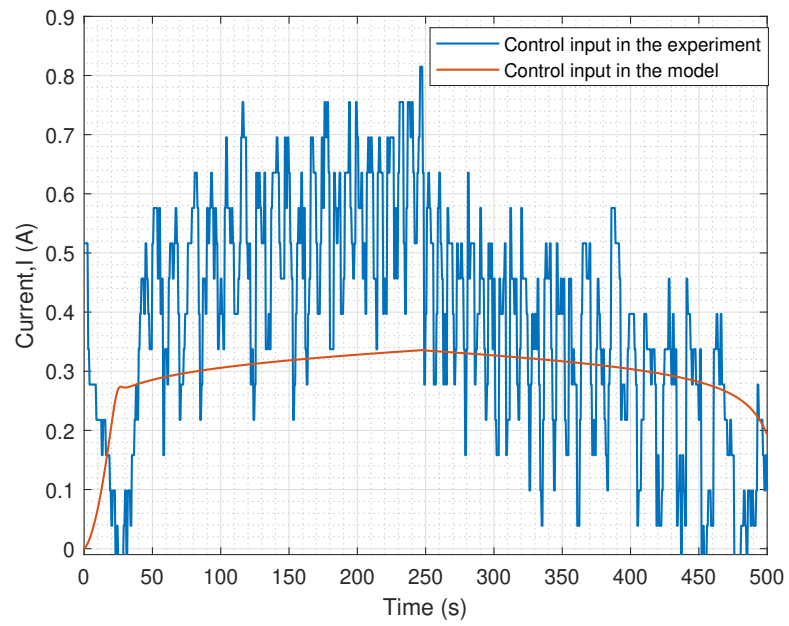


Figure 5.5 Triangular strain reference control results for the model and the experiment



(a)



(b)

Figure 5.6 Control inputs for the control action in figure 5.5:(a) duty cycle % and (b) corresponding current

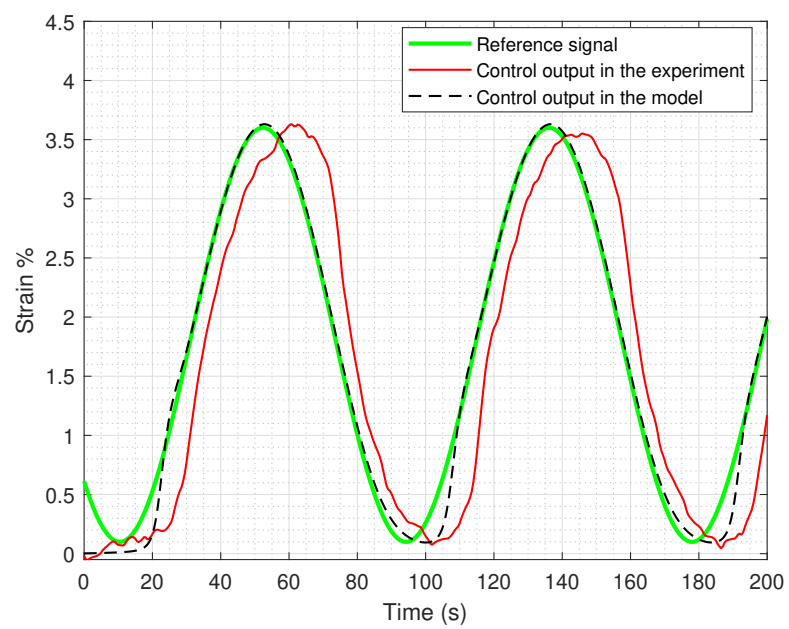
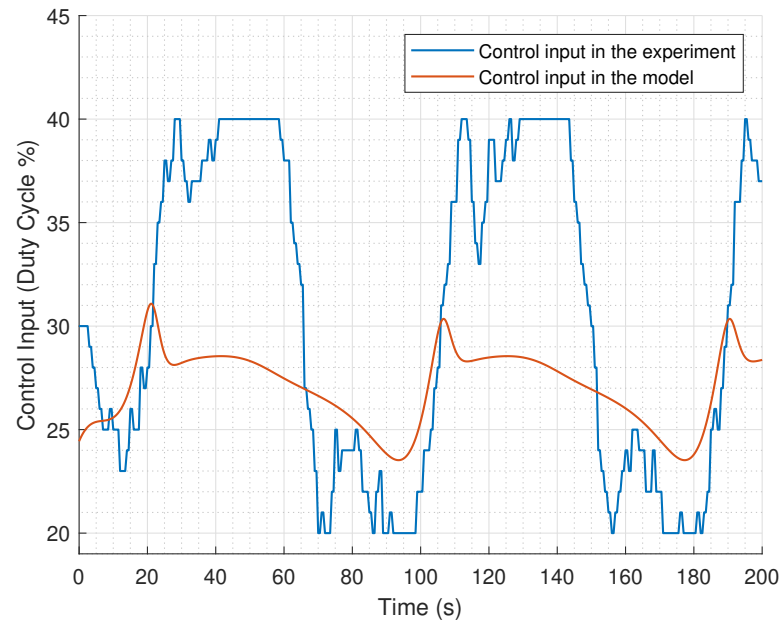
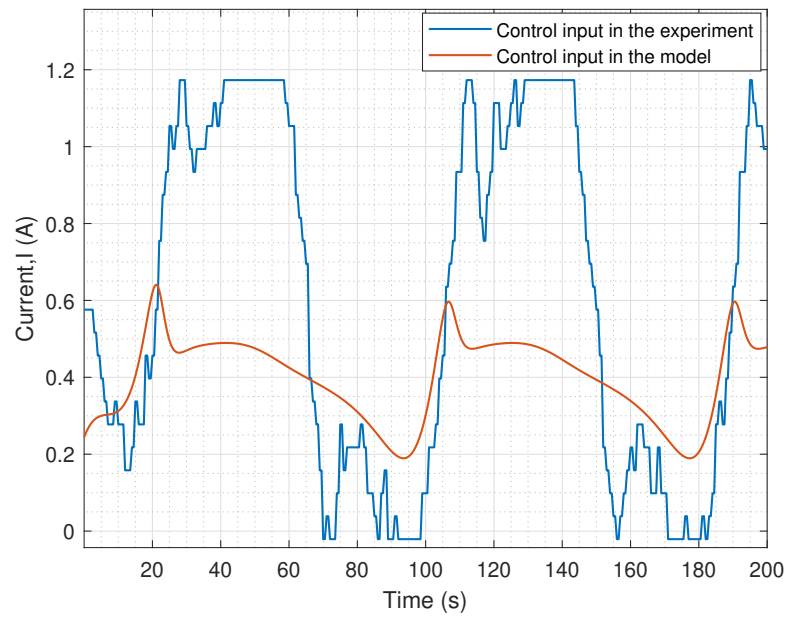


Figure 5.7 Sine strain reference control results for the model and the experiment



(a)



(b)

Figure 5.8 Control inputs for the control action in figure 5.7 (a) duty cycle % and (b) corresponding current

### **5.3. Control Action For Different Partitions Of The Wire Hysteresis**

In this section, reference signals are separately created for largely martensite, phase transition and largely austenite regions. Thus, considering the hysteresis curve of the SMA wire, it is desired to observe whether there are different regions being better for tracking or the control action is affected by phase transition and finally, whether the control performance is efficient without re-tuning.

The control exhibits delay at low strains under 0.5% because especially actual current is not sensitive to lower step change than 0.064 as mentioned previously. Also, in the beginning of the motion, the system has to overcome the friction and relative motion between the rope and the pulley. It causes a delay in actuation.

As mentioned above, actual current is not sensitive to lower step change than 0.064 as mentioned previously. However, the model can provide continuous current. Although, the current works in increase/decrease mode in the experiment. Additionally, connecting cables cause loss of energy in the experiment. Therefore, average duty cycle control input and electrical current for the model can be observed lower than the one in the actual system.

Cooling starts after 250th second in the triangular signal in figure 5.5 and firstly 52nd second in the sine signal in figure 5.7. Cooling is just provided with natural convection in this study, so, cooling takes time although the current falls back fast. Therefore, the tracking error is observed due to the delay.

#### **5.3.1. Control for Step Response**

According to figure 5.1, step reference signals are determined as the distance of 0.49mm (or strain of 0.5%) for largely martensite part, the distance of 2mm (or strain of 2%) for phase transient part and the distance of 3.35mm (or strain of 3.35%) for largely austenite part, respectively.

2% strain reference draws instantaneous current, although this causes overshoot, it reduces the rise time. 3% strain is the most distant demand and has high rise and settling time due to heating time. The increase in the average currents for all step references, except the instantaneous current part of 2% strain reference, can be seen in figure 5.10, 5.12 and 5.14.

As long as reference strain increases, the time to reach to this value also increases. Its effect can be observed on norm errors in figure 5.15. According to this, norm errors of the responses of 0.5% reference and 2% reference are close to each other in spite of the fact that the norm error of 2% reference is higher. As regards to 3.35% reference strain, it has large increase in norm error because of high rise time.

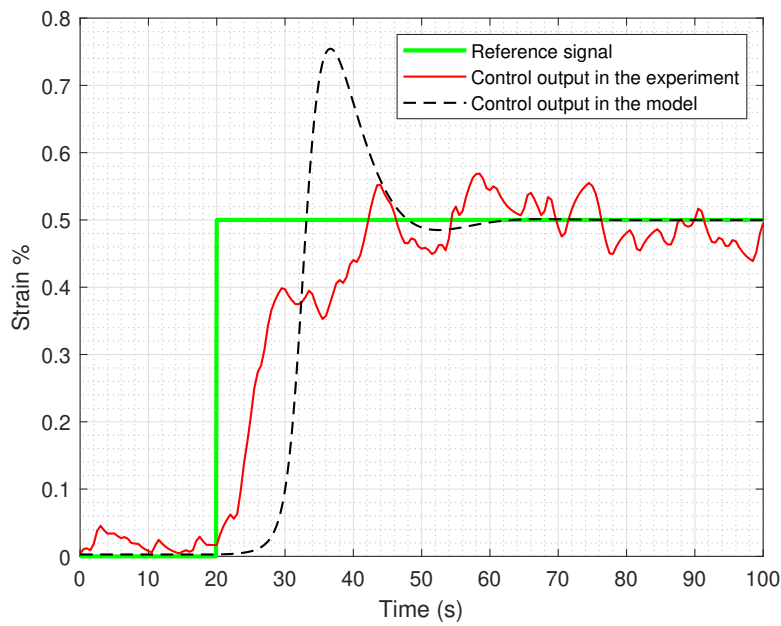
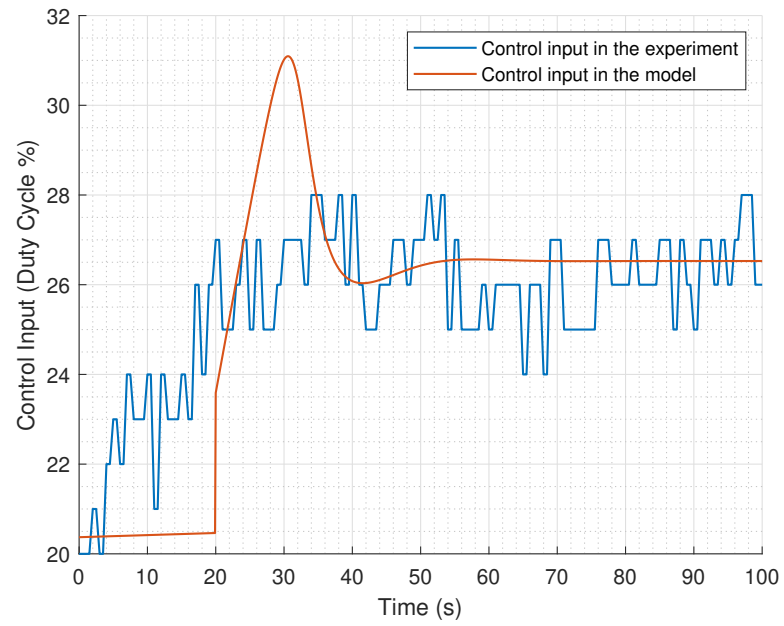
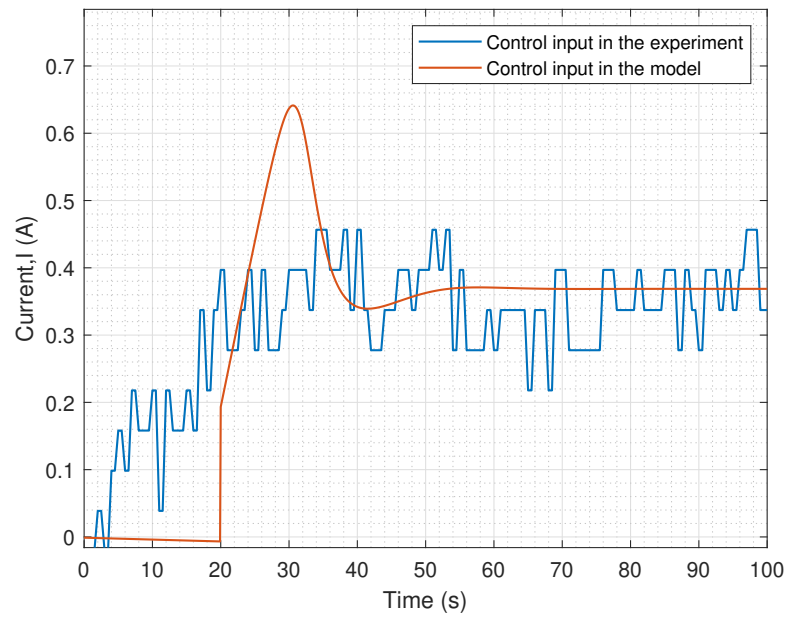


Figure 5.9 0.5% step strain reference control results for the model and the experiment



(a)



(b)

Figure 5.10 Control inputs for the control action in figure 5.9: (a) duty cycle % and (b) corresponding current

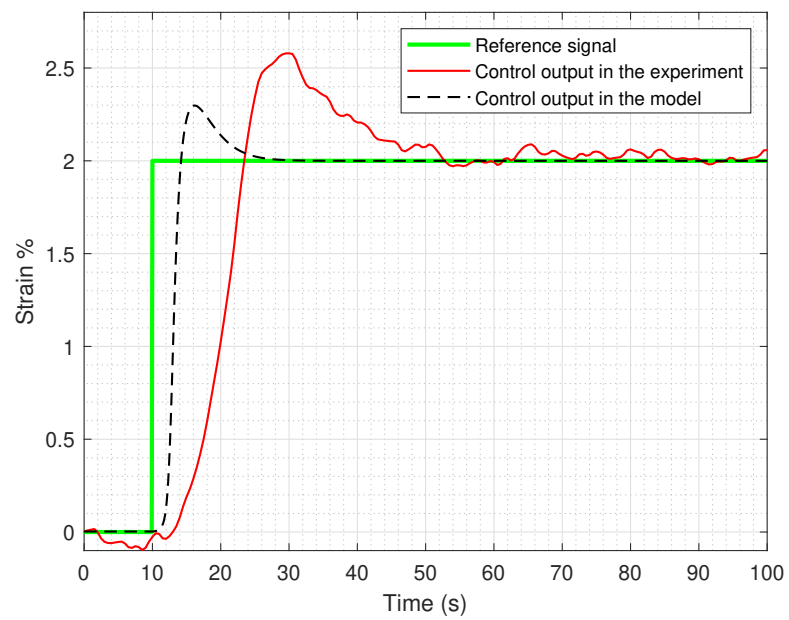
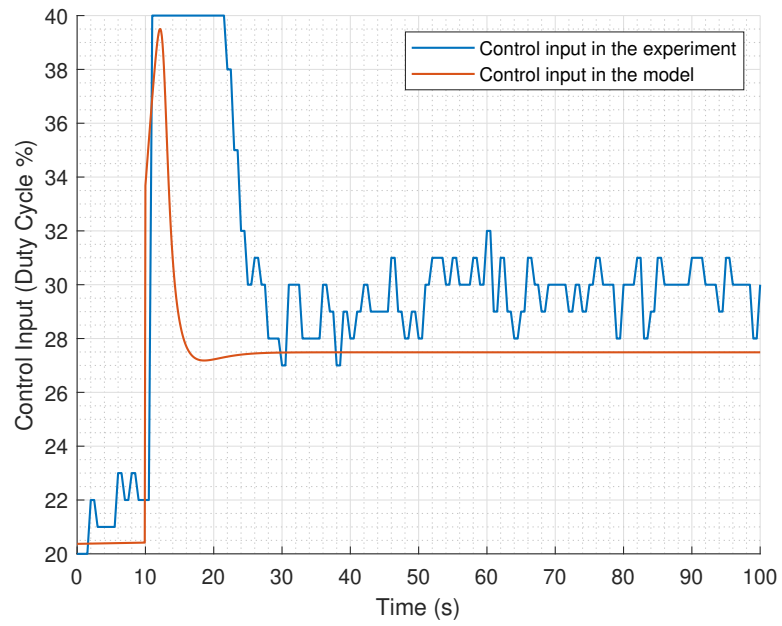
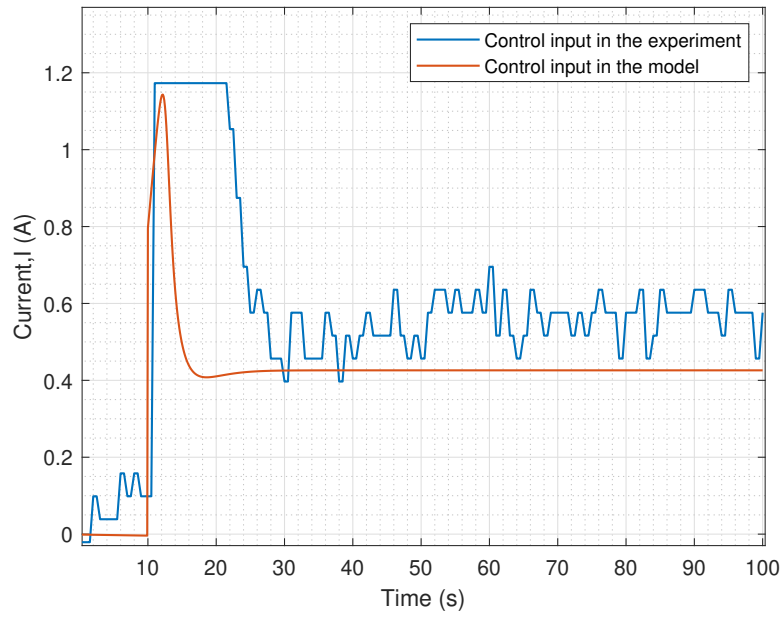


Figure 5.11 2% step strain reference control results for the model and the experiment



(a)



(b)

Figure 5.12 Control inputs for the control action in figure 5.11:(a) duty cycle % and (b) corresponding current

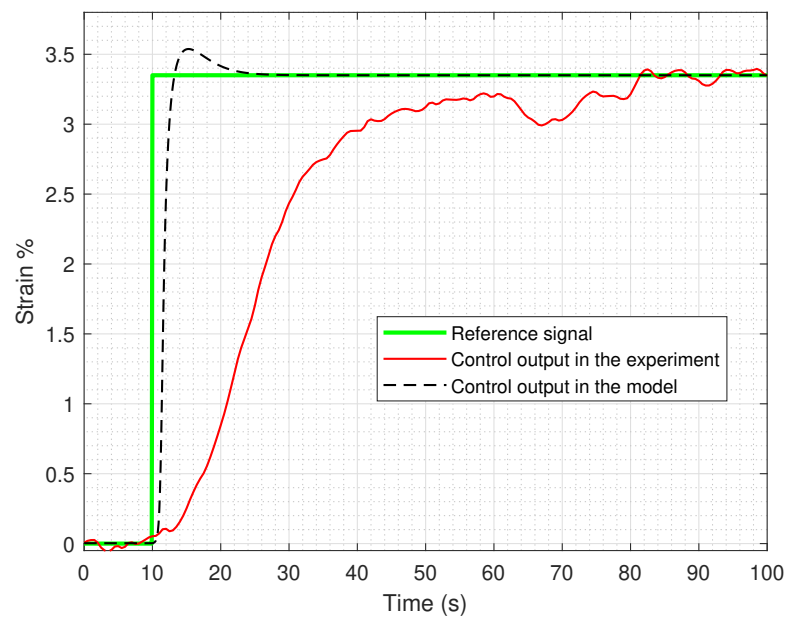
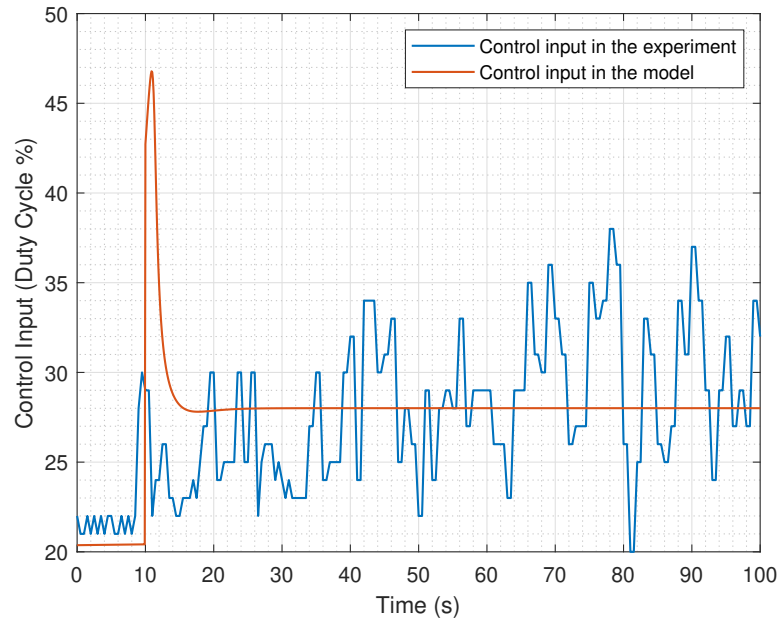
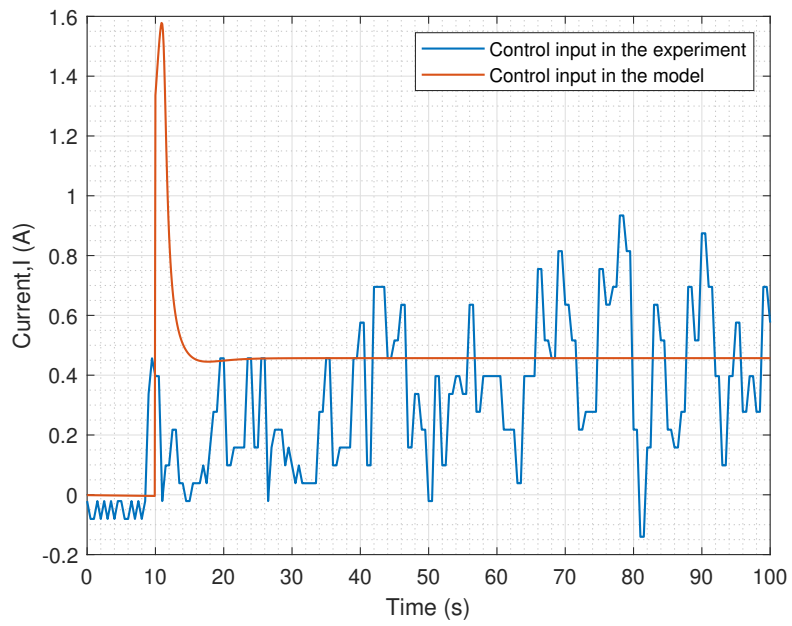


Figure 5.13 3.35% step strain reference control results for the model and the experiment



(a)



(b)

Figure 5.14 Control inputs for the control action in figure 5.13: (a) duty cycle % and (b) corresponding current

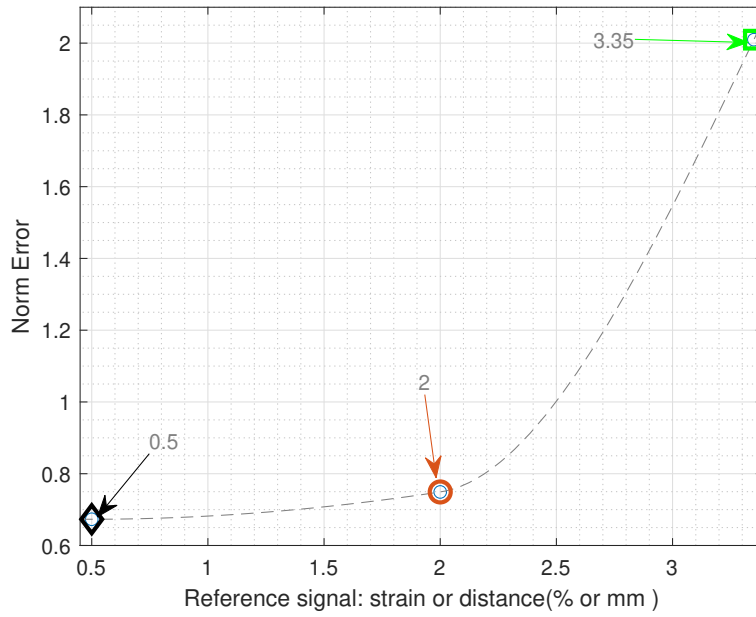


Figure 5.15 Norm errors for the step strain references

### 5.3.2. Control for Sine Response

In this section, sine strain references are given to the system. Their equilibrium lines are the same with the step references in the previous section, i.e. 0.5%, 2% and 3.35% respectively. Also, the desired inputs are restricted into largely martensite, phase transient and largely austenite regions by taking amplitudes of the sine references as 0.25%. Effects of increasing frequencies on the tracking performances are discussed in this section as well.

Tracking can be seen in figures 5.16, 5.18, 5.20, 5.22, 5.24, 5.26, 5.28, 5.30, 5.32, 5.34, 5.36 and 5.38 and duty cycle % with corresponding electrical current is given in figures 5.17, 5.19, 5.21, 5.23, 5.25, 5.27, 5.29, 5.31, 5.33, 5.35, 5.37 and 5.39.

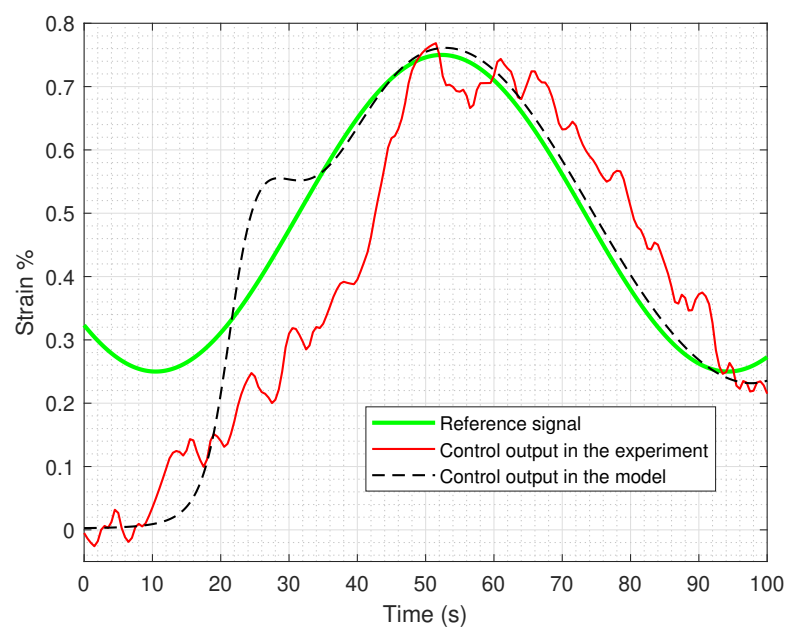
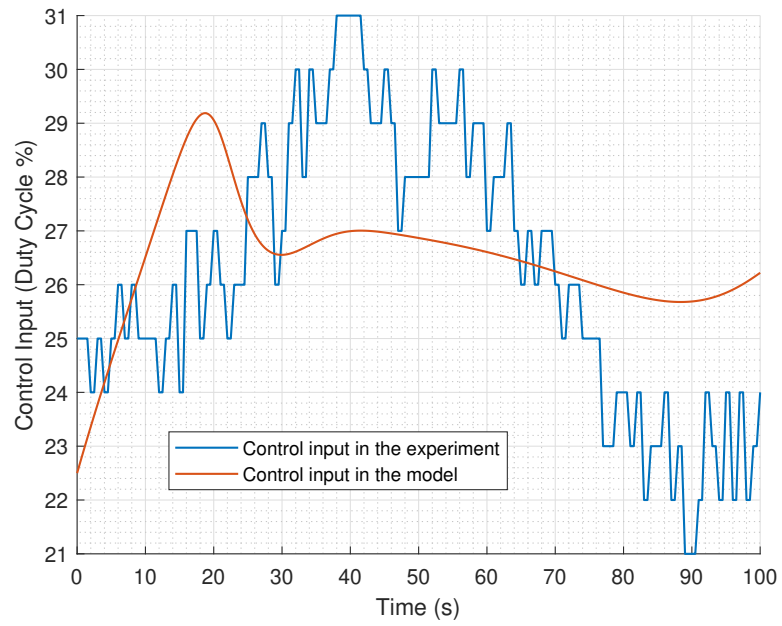
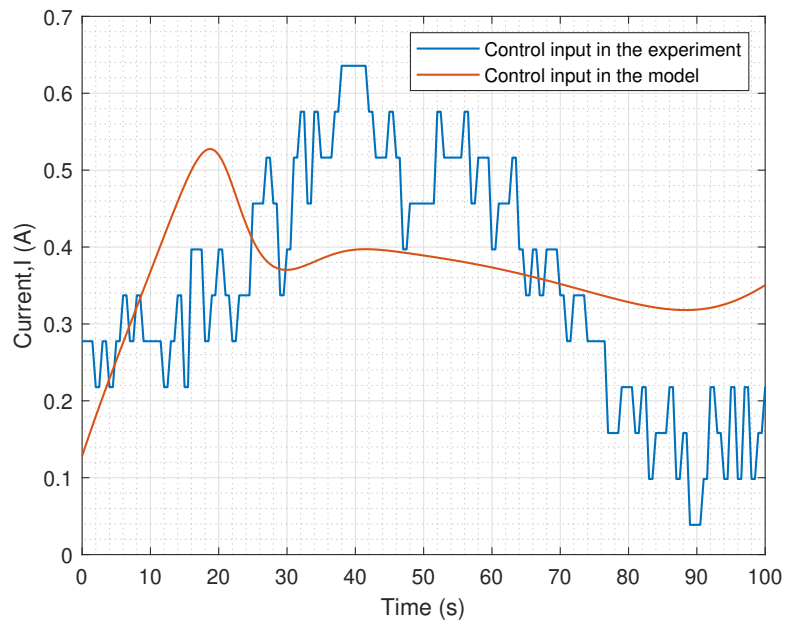


Figure 5.16 Sine strain reference control with the equilibrium line of 0.5 mm and the frequency of 0.075 rad/s



(a)



(b)

Figure 5.17 Control inputs for the control action in figure 5.16:(a) duty cycle % and (b) corresponding current

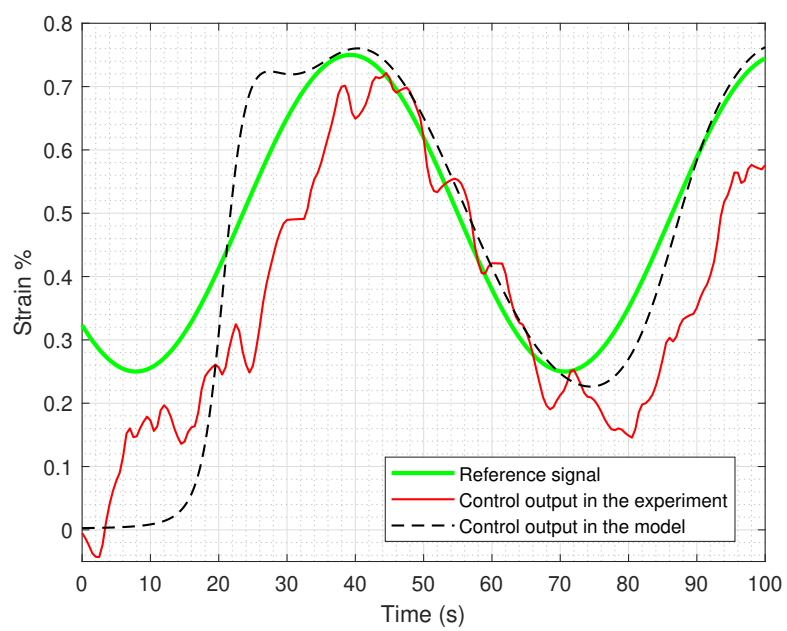
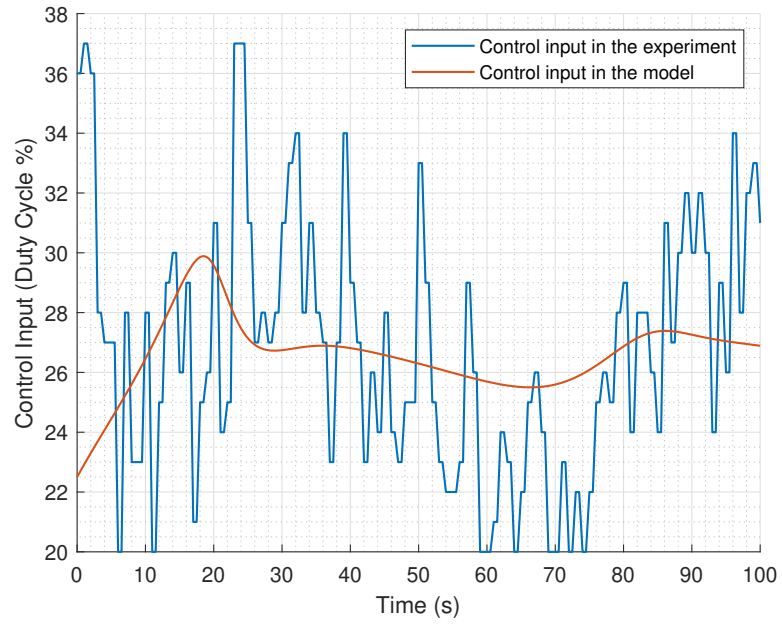
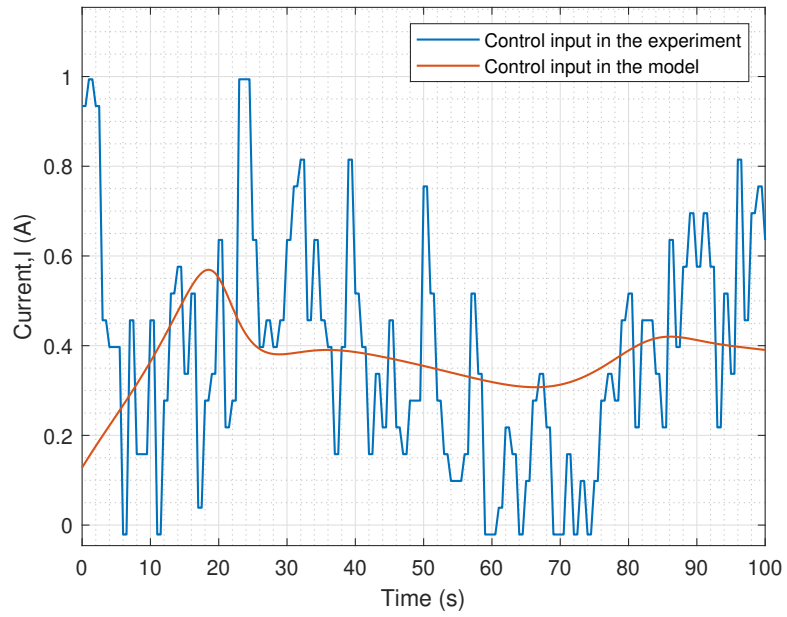


Figure 5.18 Sine strain reference control with the equilibrium line of 0.5 mm and the frequency of 0.1 rad/s



(a)



(b)

Figure 5.19 Control inputs for the control action in figure 5.18:(a) duty cycle % and (b) corresponding current

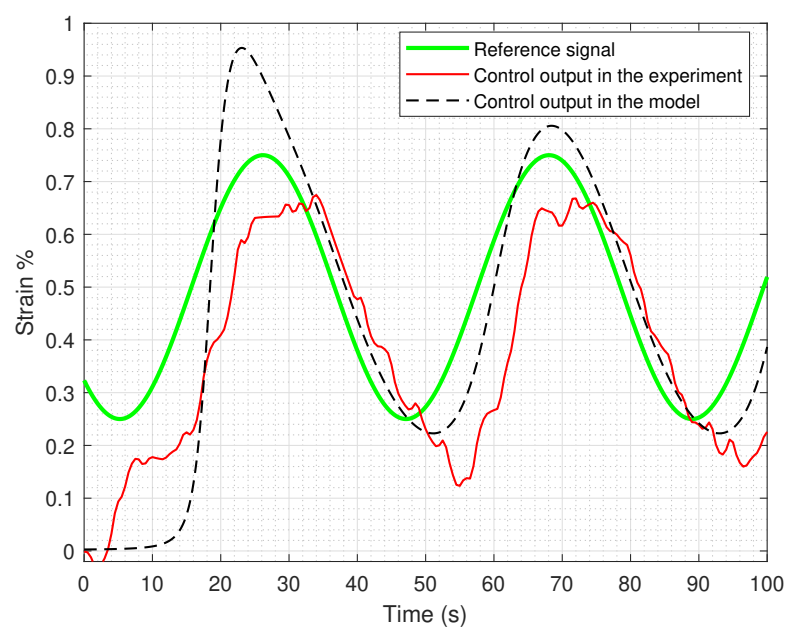
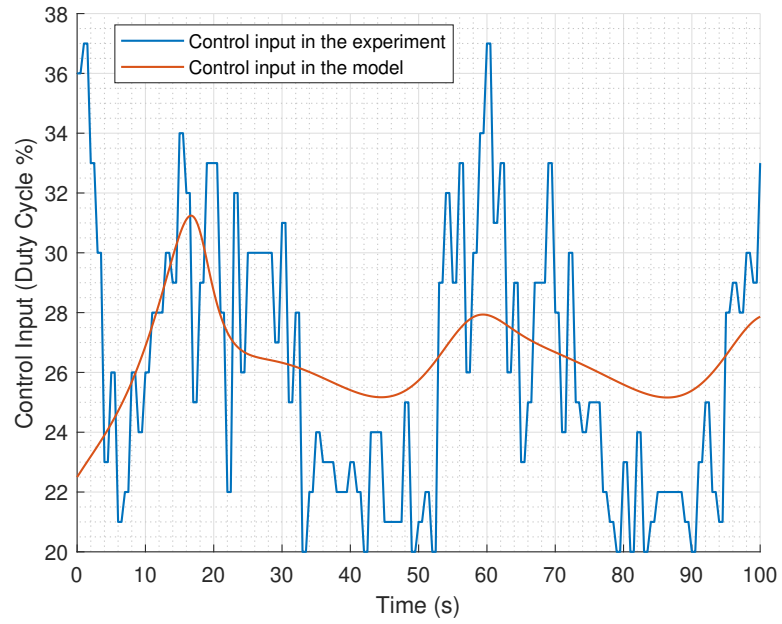
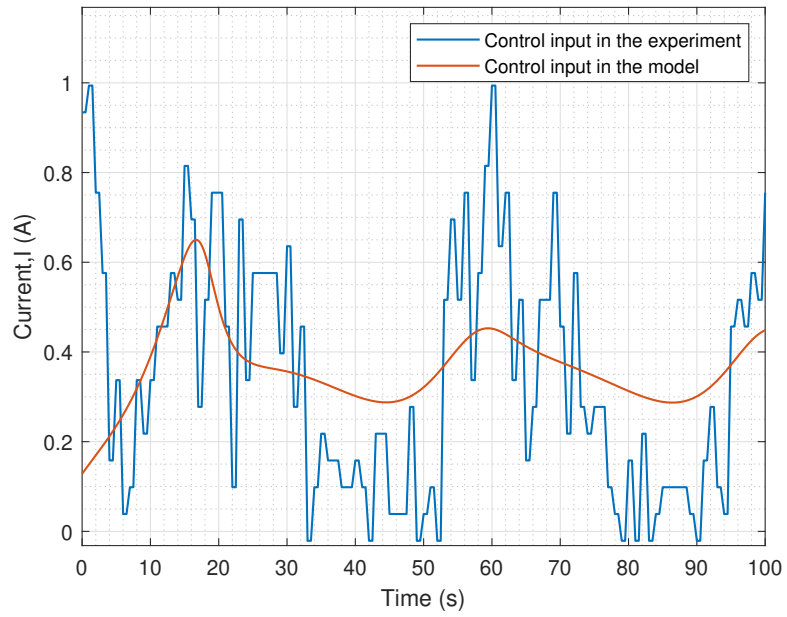


Figure 5.20 Sine strain reference control with the equilibrium line of 0.5 mm and the frequency of 0.15 rad/s



(a)



(b)

Figure 5.21 Control inputs for the control action in figure 5.20:(a) duty cycle % and (b) corresponding current

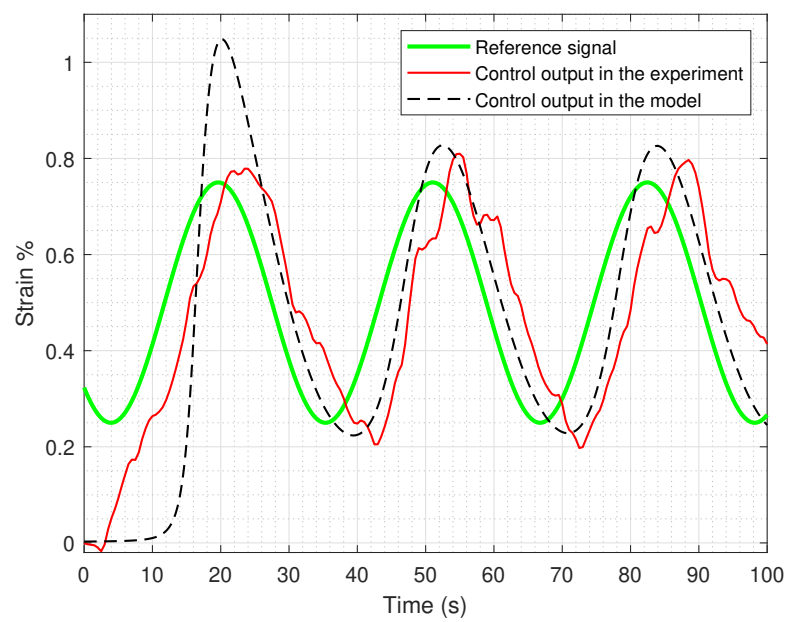
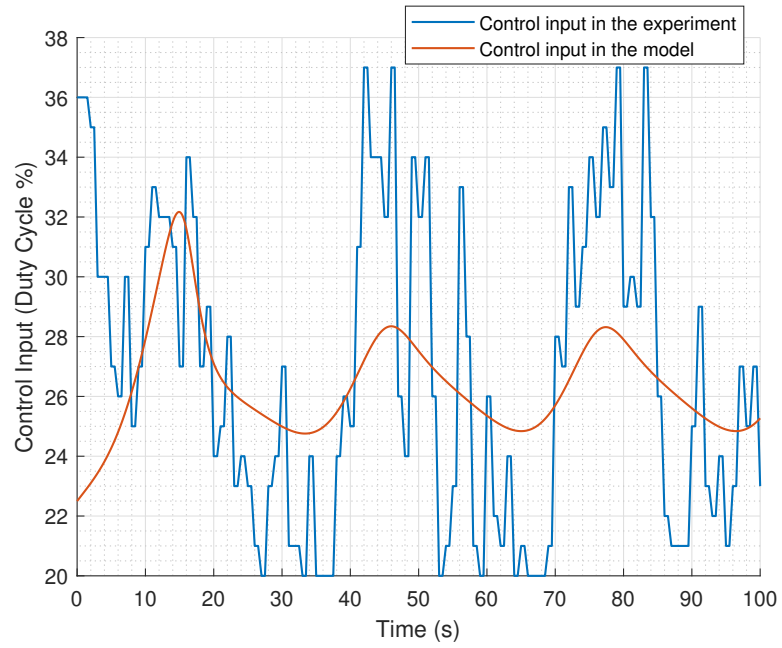
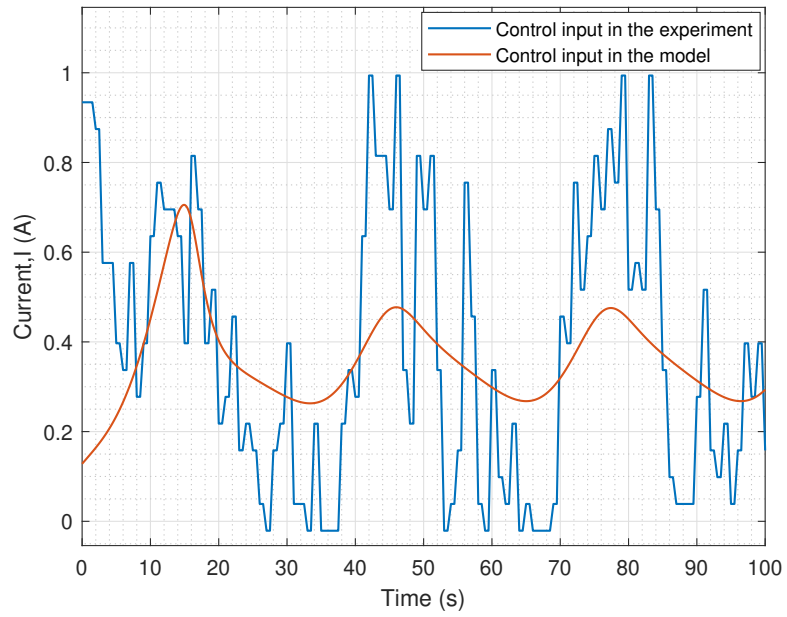


Figure 5.22 Sine strain reference control with the equilibrium line of 0.5 mm and the frequency of 0.2 rad/s



(a)



(b)

Figure 5.23 Control inputs for the control action in figure 5.22:(a) duty cycle % and (b) corresponding current

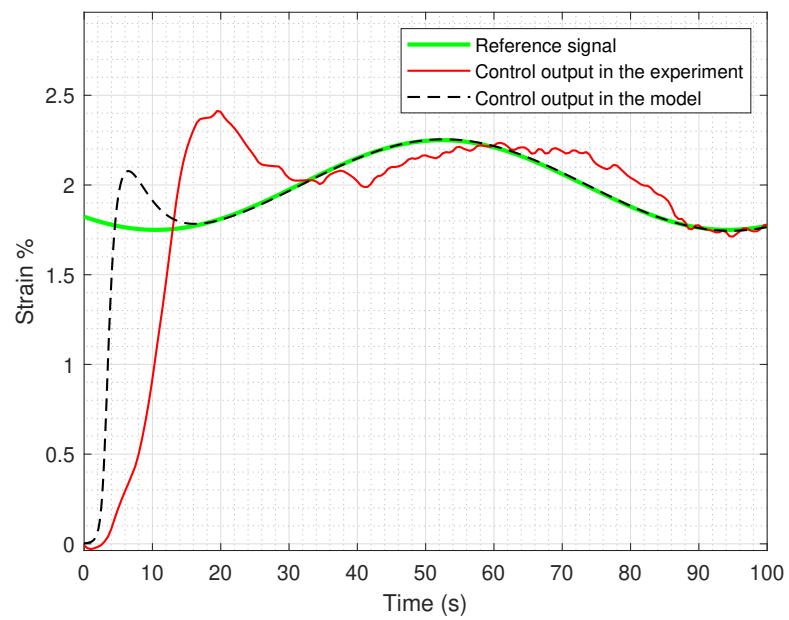
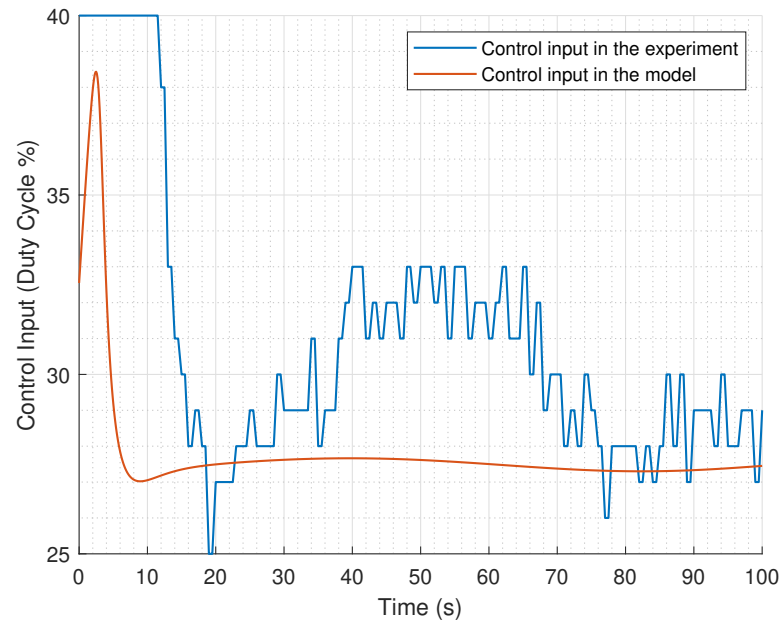
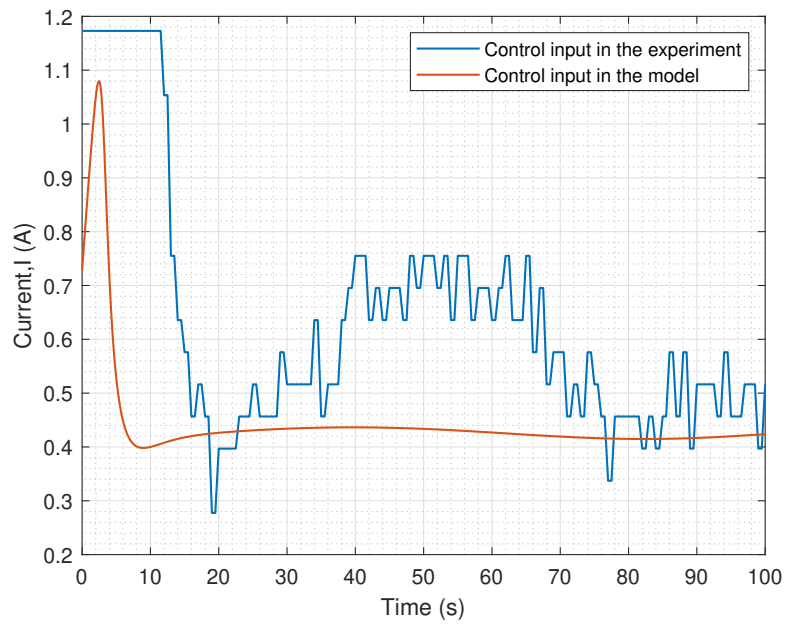


Figure 5.24 Sine strain reference control with the equilibrium line of 2 mm and the frequency of 0.075 rad/s



(a)



(b)

Figure 5.25 Control inputs for the control action in figure 5.24:(a) duty cycle % and (b) corresponding current

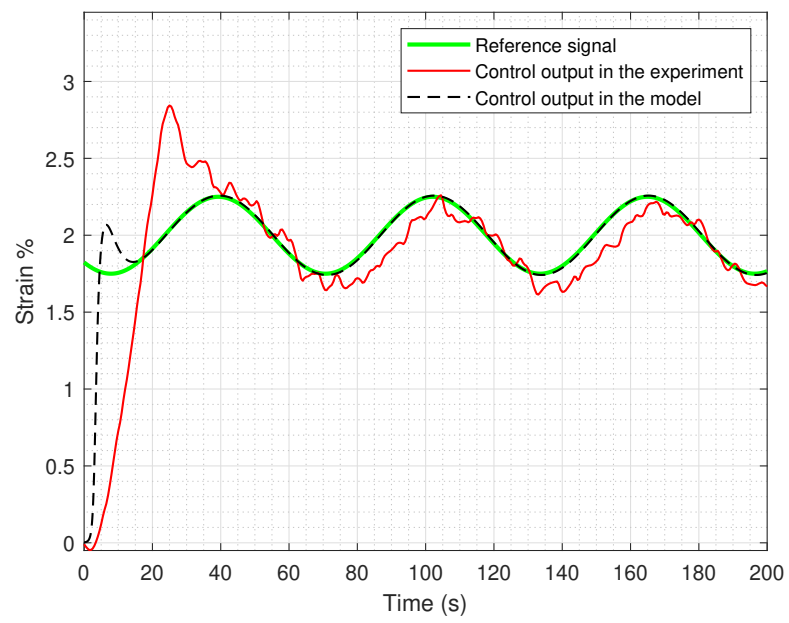
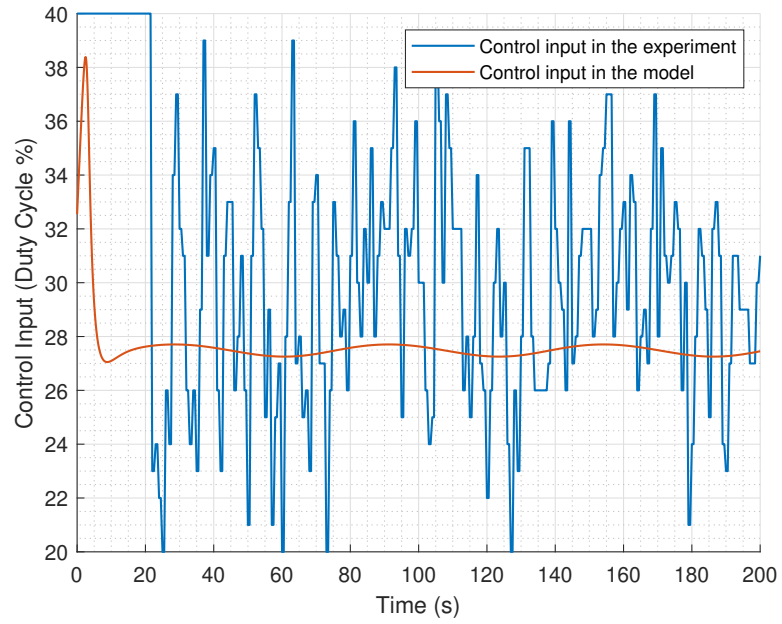
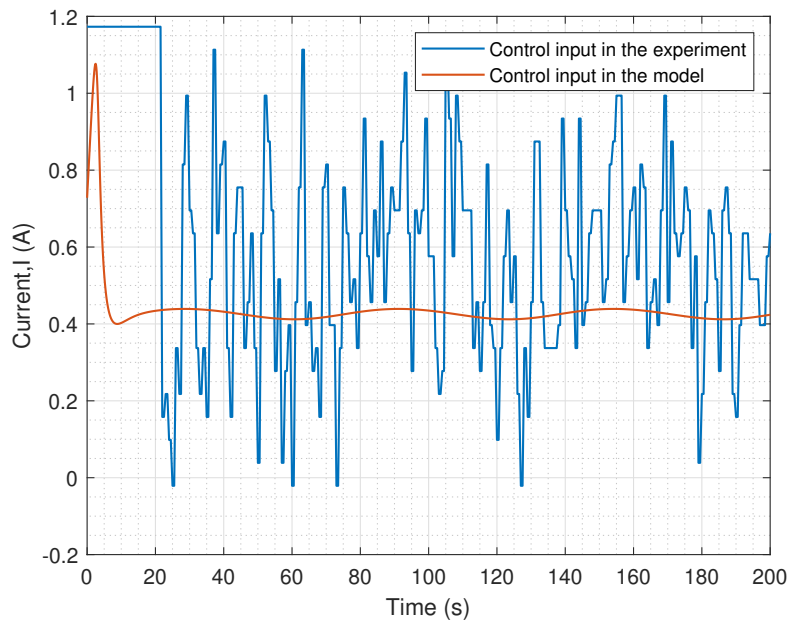


Figure 5.26 Sine strain reference control with the equilibrium line of 2 mm and the frequency of 0.1 rad/s



(a)



(b)

Figure 5.27 Control inputs for the control action in figure 5.26:(a) duty cycle % and (b) corresponding current

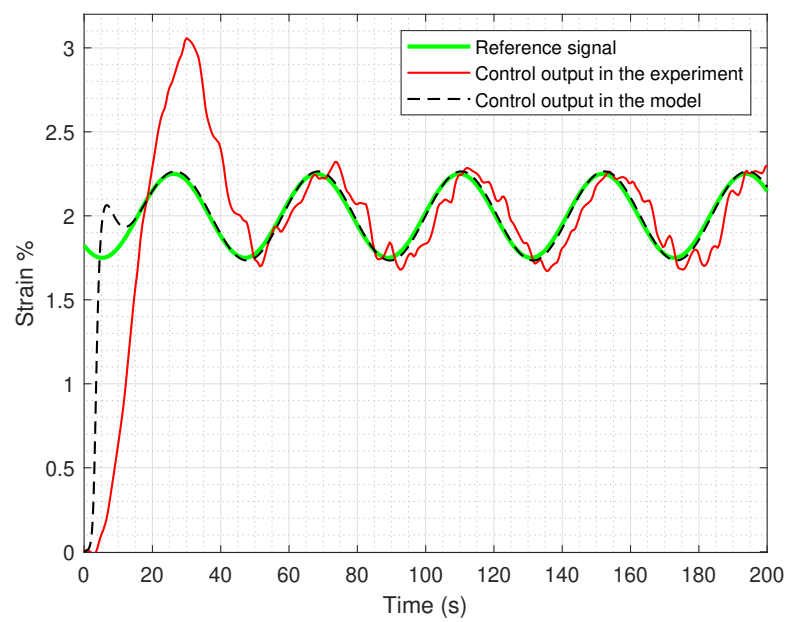
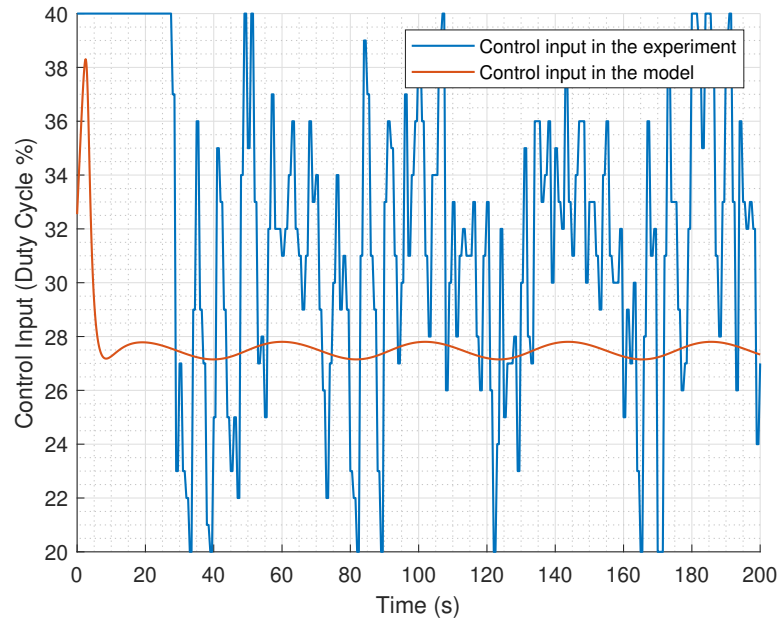
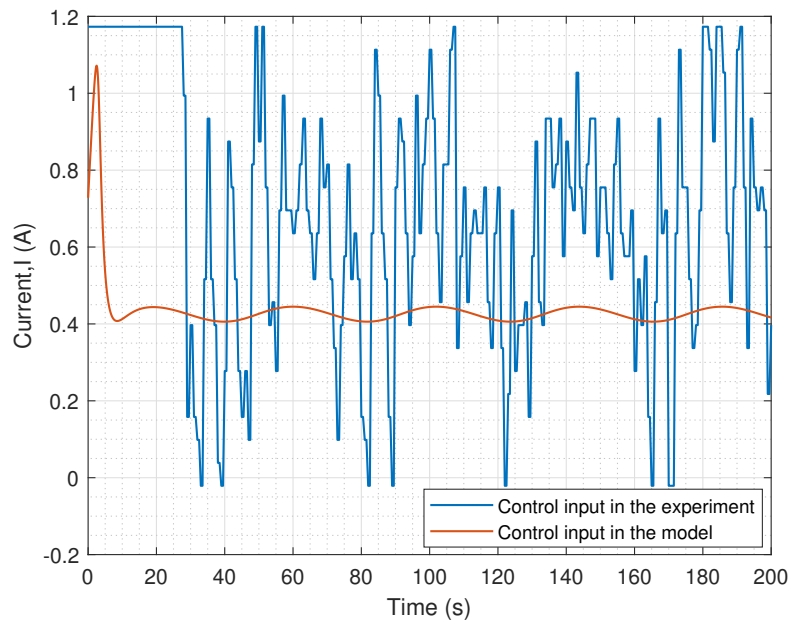


Figure 5.28 Sine strain reference control with the equilibrium line of 2 mm and the frequency of 0.15 rad/s



(a)



(b)

Figure 5.29 Control inputs for the control action in figure 5.28:(a) duty cycle % and (b) corresponding current

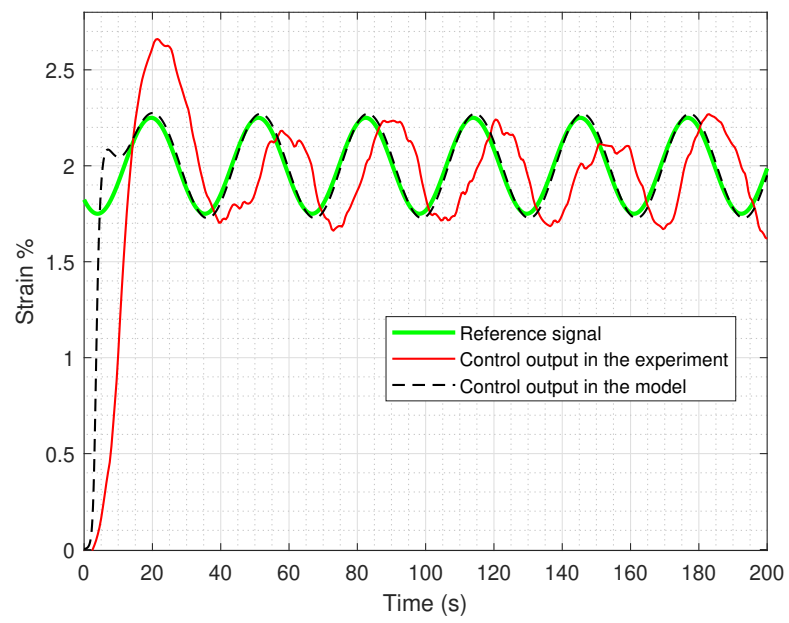
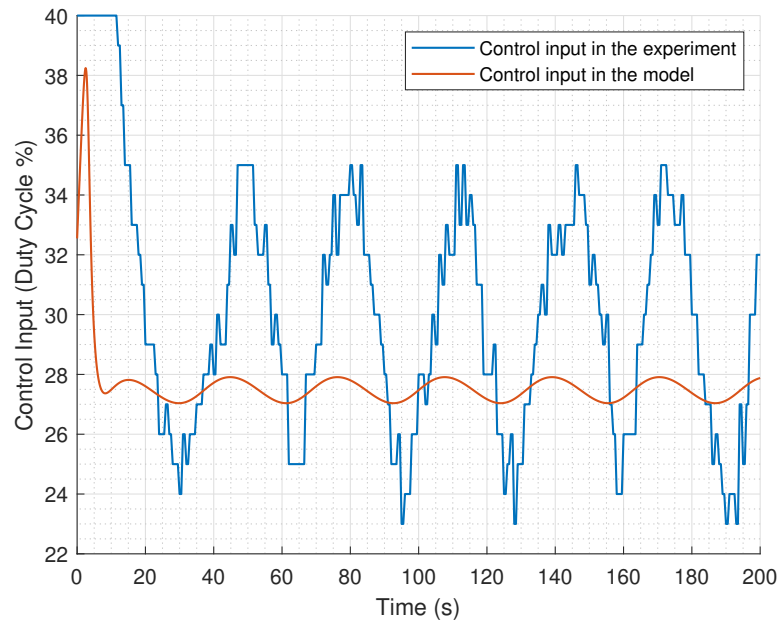
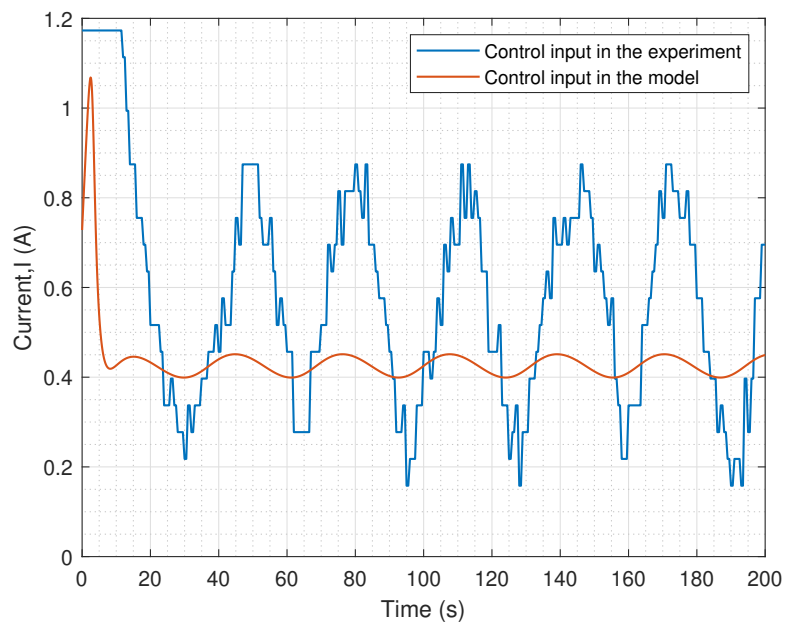


Figure 5.30 Sine strain reference control with the equilibrium line of 2 mm and the frequency of 0.2 rad/s



(a)



(b)

Figure 5.31 Control inputs for the control action in figure 5.30:(a) duty cycle % and (b) corresponding current

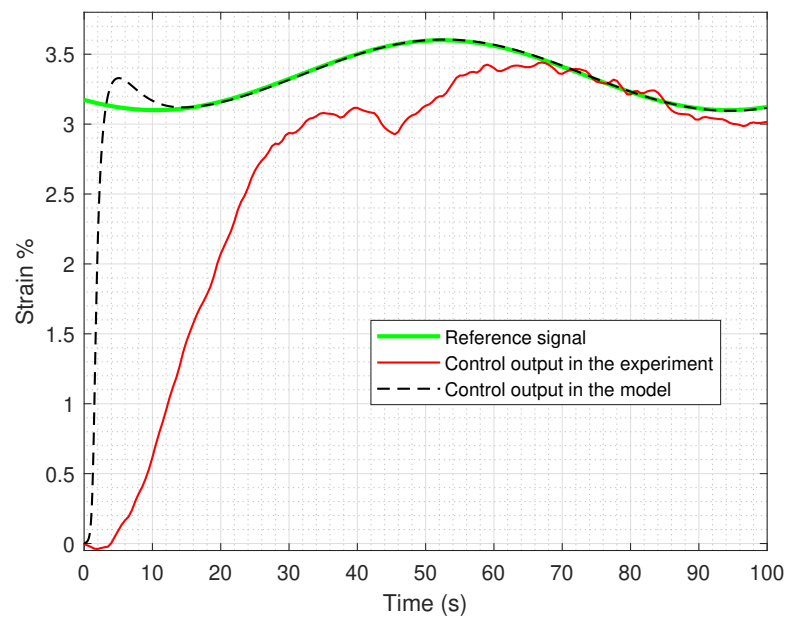
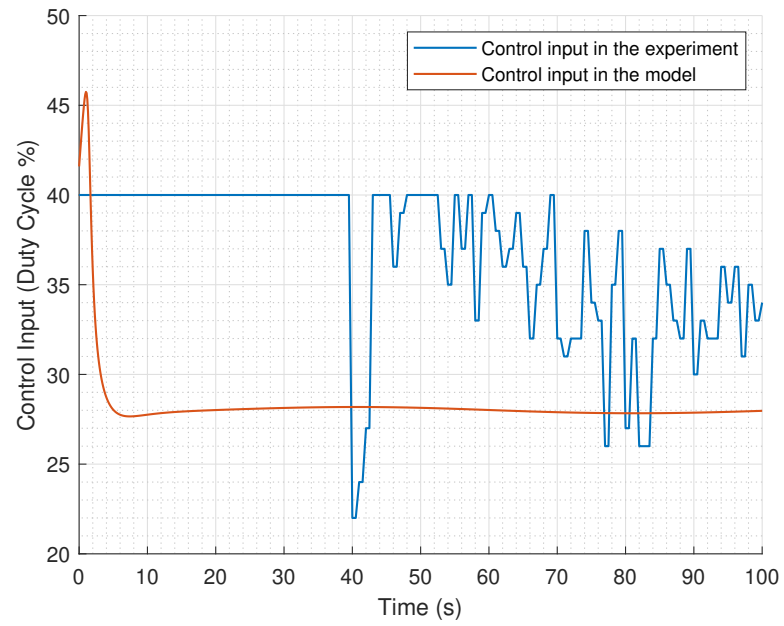
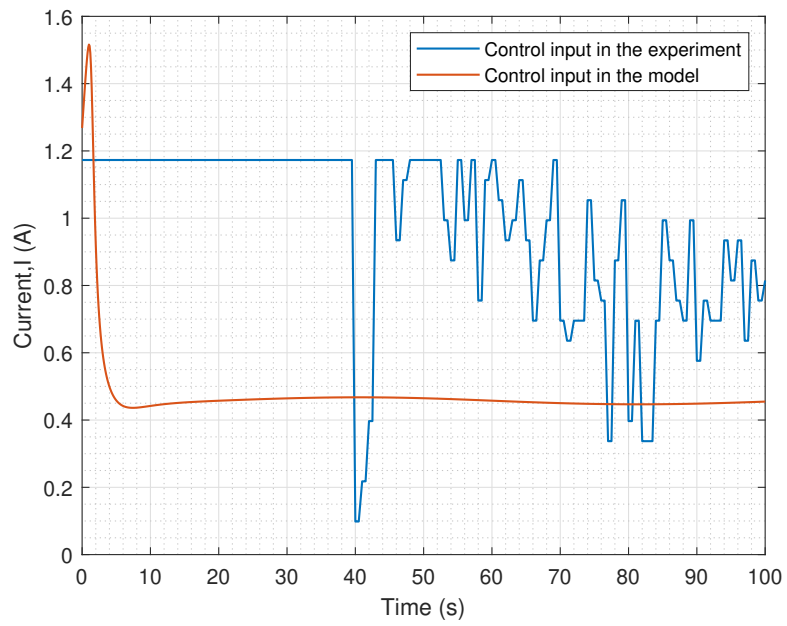


Figure 5.32 Sine strain reference control with the equilibrium line of 3.35 mm and the frequency of 0.075 rad/s



(a)



(b)

Figure 5.33 Control inputs for the control action in figure 5.32:(a) duty cycle % and (b) corresponding current

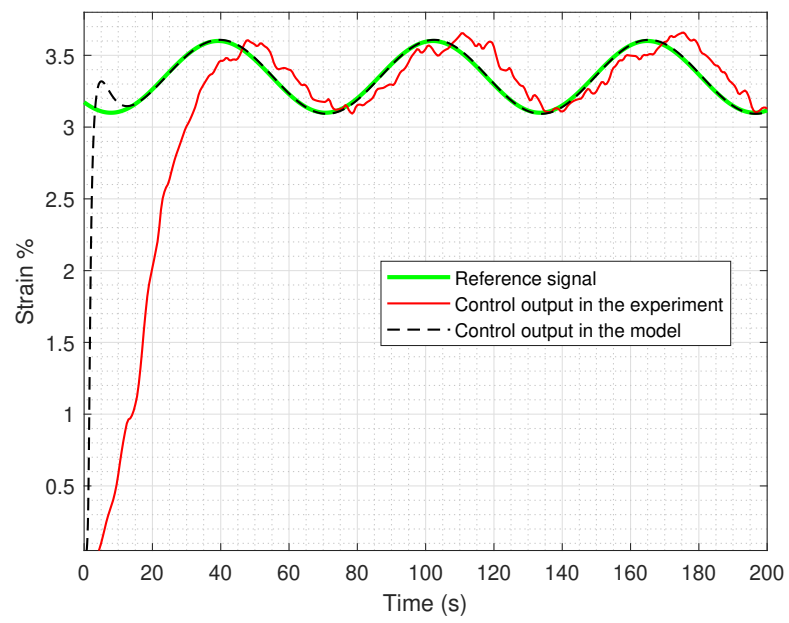
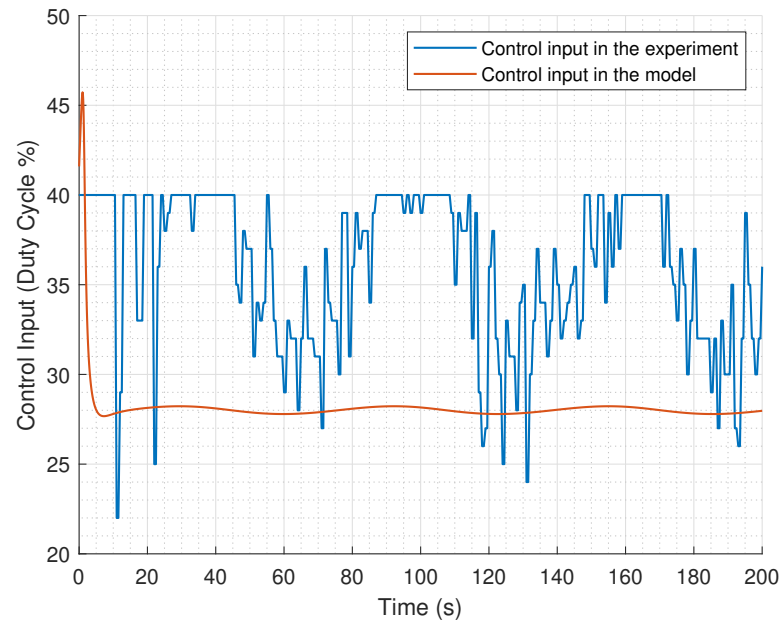
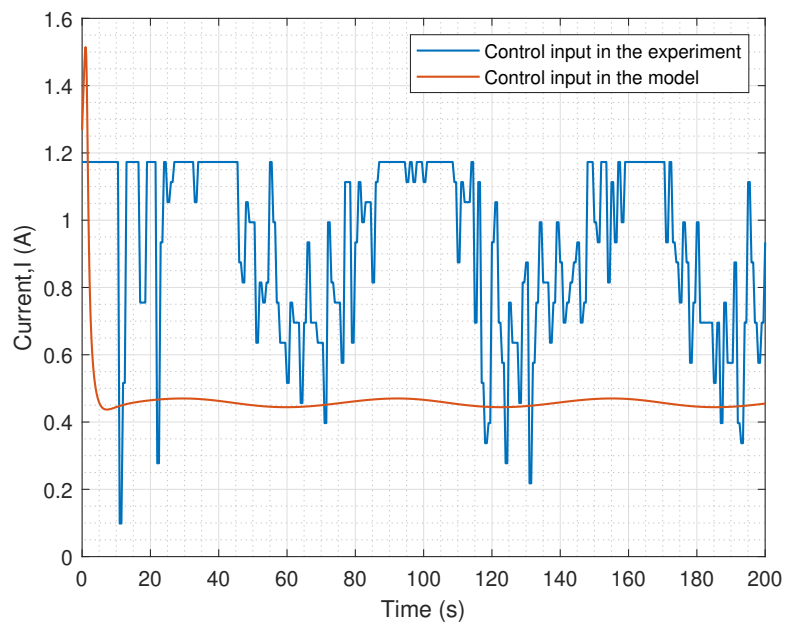


Figure 5.34 Sine strain reference control with the equilibrium line of 3.35 mm and the frequency of 0.1 rad/s



(a)



(b)

Figure 5.35 Control inputs for the control action in figure 5.34:(a) duty cycle % and (b) corresponding current

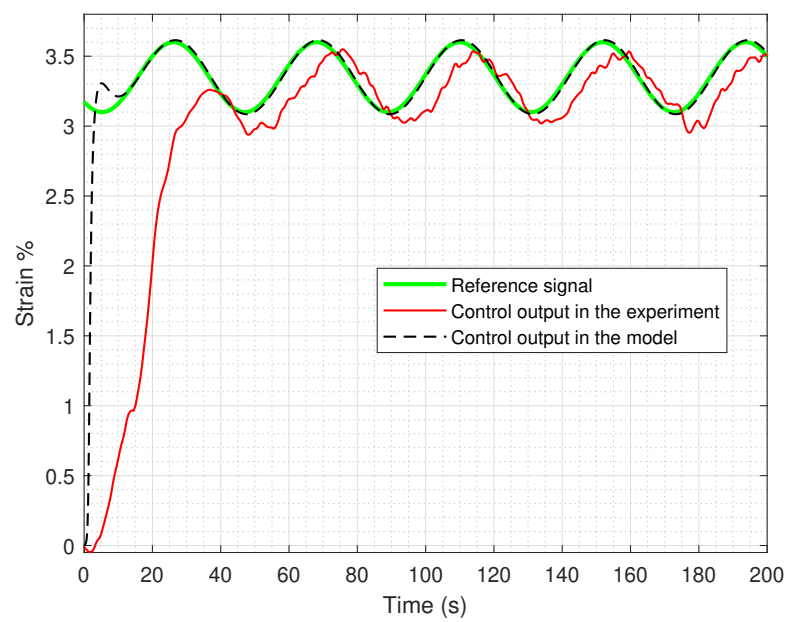
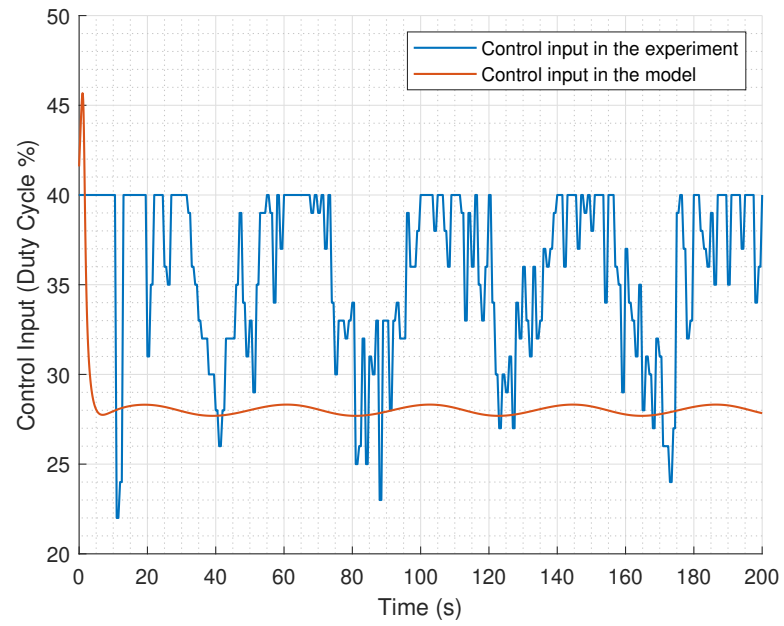
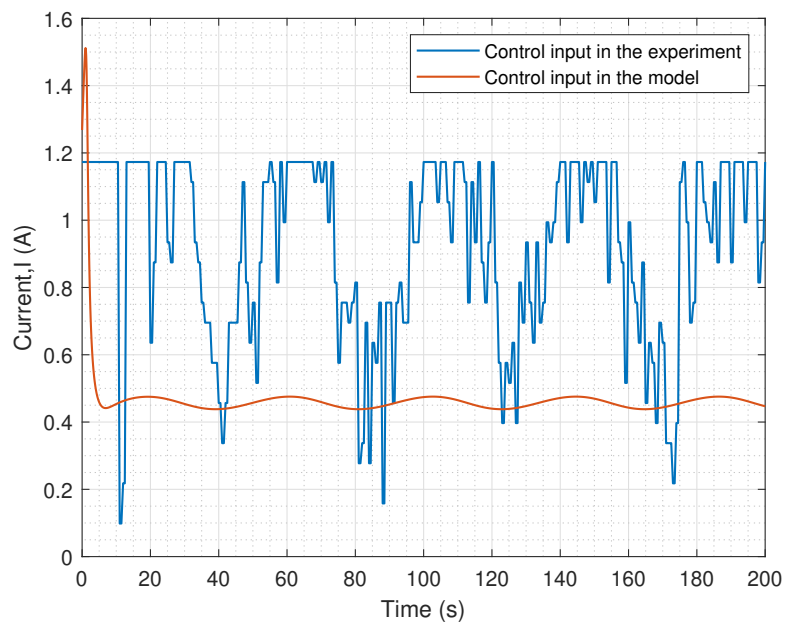


Figure 5.36 Sine strain reference control with the equilibrium line of 3.35 mm and the frequency of 0.15 rad/s



(a)



(b)

Figure 5.37 Control inputs for the control action in figure 5.36:(a) duty cycle % and (b) corresponding current

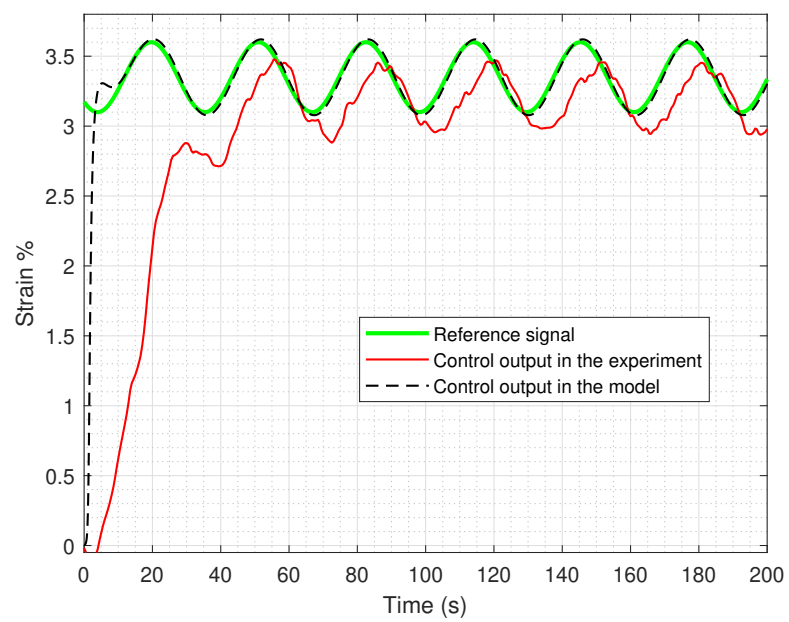
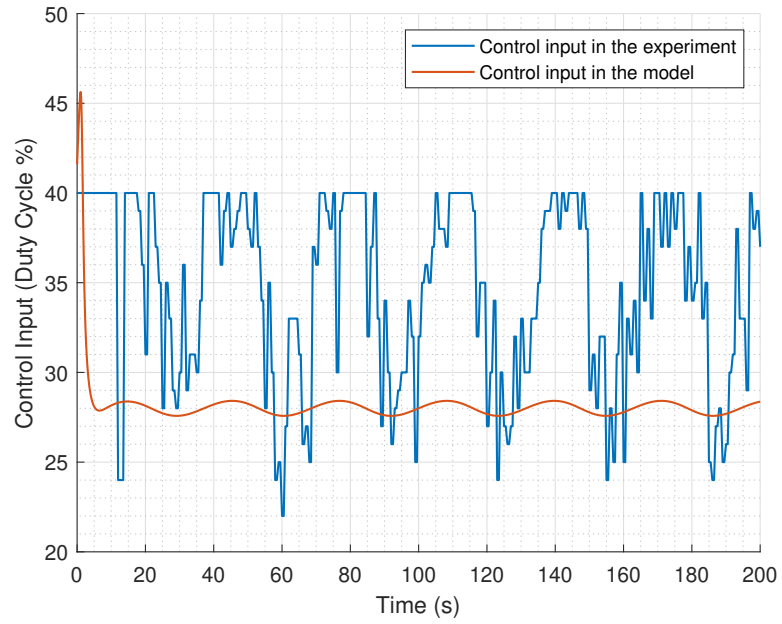
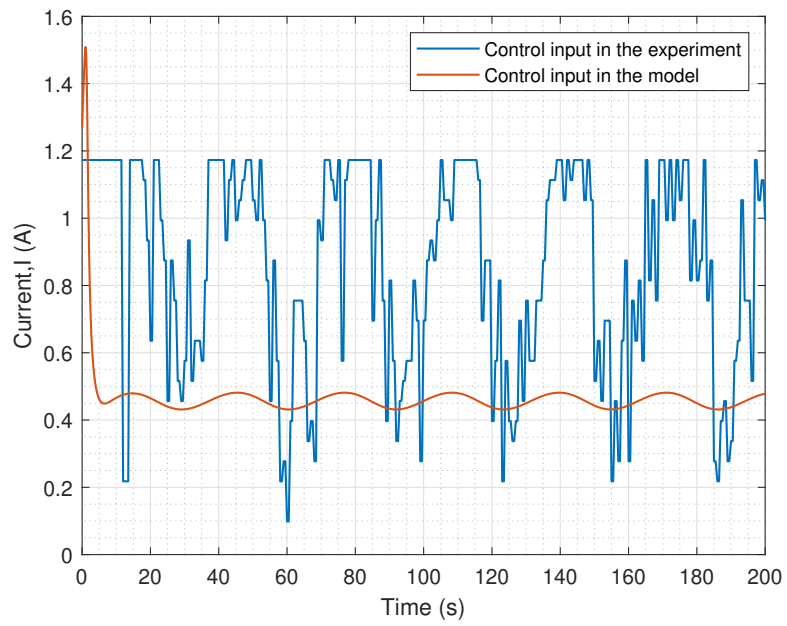


Figure 5.38 Sine strain reference control with the equilibrium line of 3.35 mm and the frequency of 0.2 rad/s



(a)



(b)

Figure 5.39 Control inputs for the control action in figure 5.38:(a) duty cycle % and (b) corresponding current

### 5.3.3. Discussion

In this section, firstly, tracking performances are discussed. Norm errors related to the increasing frequencies for sine strain reference inputs having 0.5%, 2% and 3.35% equilibrium line are given in figure 5.40. According to this, although increase and decrease exist in norm errors for each different sine references, average errors for the sine reference with 0.5% equilibrium line and the sine reference with 3.35% equilibrium line proceed in a narrow interval between 0.7-1.6. Also, these errors come close to each other in high frequencies. However, as the error for the sine reference with 2% equilibrium line occurs with increasing frequency, this increase exhibits a major separation in the largest frequency. It can be concluded that the controller has difficulty in tracking this region where phase transition is active and during reference demand with high frequency of 0.2rad/s. Secondly, the results are evaluated in terms of control inputs, duty cycle % and corresponding currents. According to this, the steps of increase in duty cycle get fast. The inputs pass from frequent increasing/decreasing behaviour to fast steps during increasing/decreasing, in other words, the wait time in any constant duty cycle is reduced. The reference signal with the equilibrium line of 2% has fast passing between steps of duty cycles. In spite of that, the number of steps in increasing/decreasing for the reference signal with the equilibrium line of 0.5% is low. It tends to wait for a longer period of time at the certain duty cycle. When the reference signal is with the equilibrium line of 3.35%, the control input has tendency to reach to the saturated high electrical current and stay there. The quick decrease from high duty cycle % is observed in this case.

In conclusion, in general meaning, the controller performance is effective without return of the gains for all cases, although some delay can be observed. Also, it is shown in the next section by testing under variable loading that the controller performance is available.

## 5.4. Control Under Variable Loading

Finally, in this section, controller performance is analyzed under variable loading. For this, a bottle has been hung from one end of the rope that the SMA wire has been connected to,

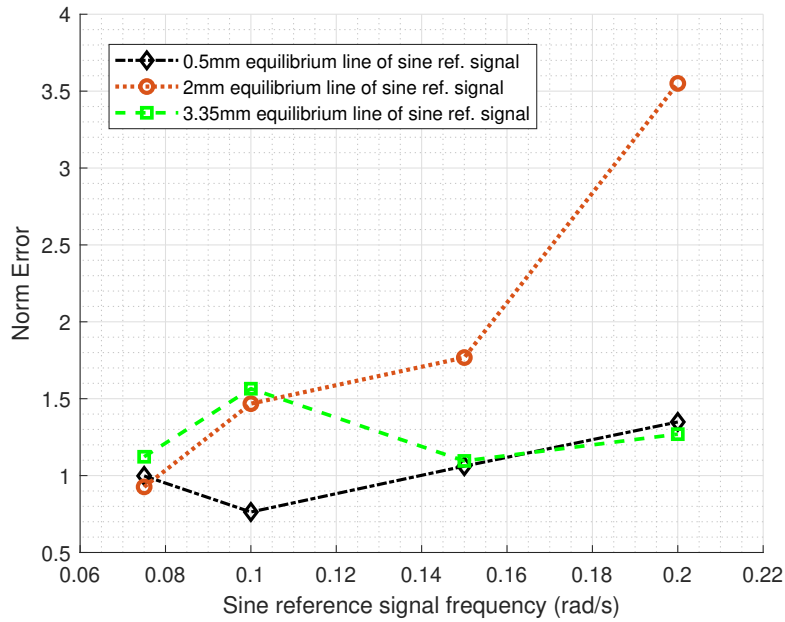


Figure 5.40 Norm errors of the control actions in different frequencies

and the other end with a dead weight as can be seen in figure 5.41. Then, the bottle has been filled with 2.2 kg of fluid. After the start of the strain control experiment, the fluid is made to begin to draining by turning the screw hook which is fixed to the bottom of the bottle as a stopper. Thus, the load is changed by reducing as can be seen in figure 5.42 and figure 5.46. The dead weights in figures are 3.1kg and 3.65kg, respectively.

Draining is started at 120th second, as can be seen from the undershoot in figure 5.41. An overshoot is observed at the time when the screw hook begins to turn in figure 5.43; except this the tracking continues. Also, the decreases in duty cycle-current and in temperature with decreasing load can be followed in figure 5.44 and figure 5.45, respectively.

Draining is started at 300th second, as can be seen in figure 5.46 for the sine reference signal scanning the hysteresis curve completely. Decrease of just 2-3 N before this second is due to measurement error of the load cell. Also, this draining is faster than the previous one. An overshoot is observed in the time when the screw hook starts to be turned in figure 5.47 and except this the tracking continues. Also, the decreases in duty cycle-current and in temperature with decreasing load can be followed in figure 5.48 and figure 5.49, respectively.

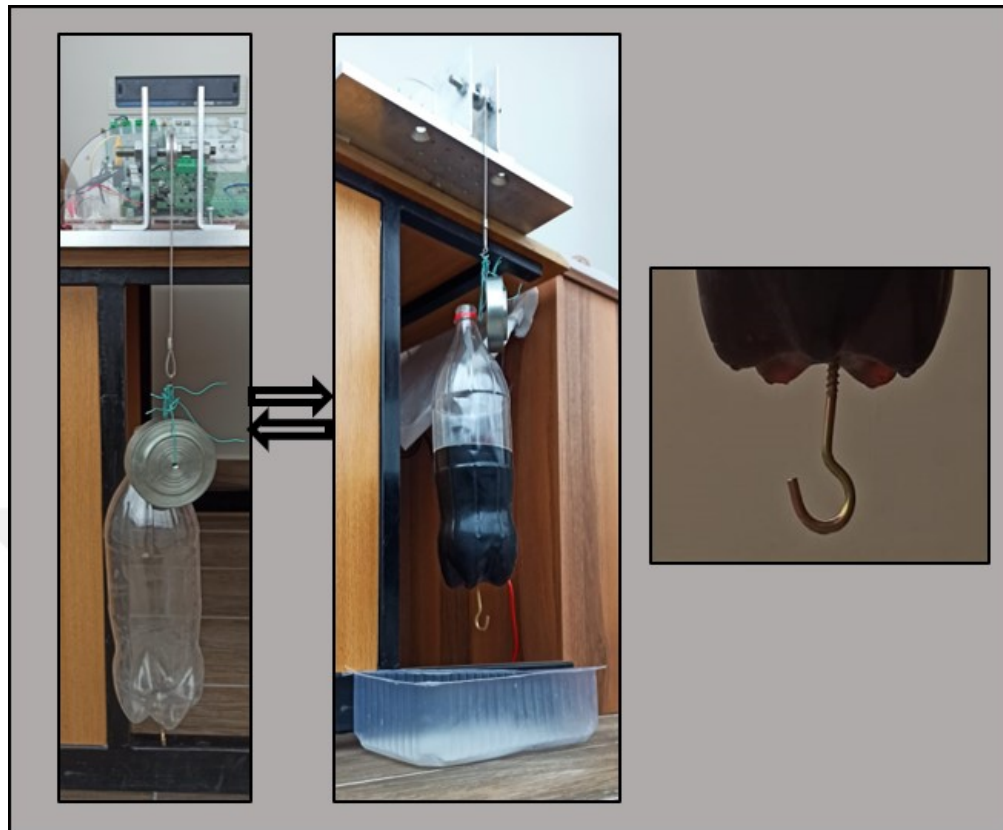


Figure 5.41 System for variable loading

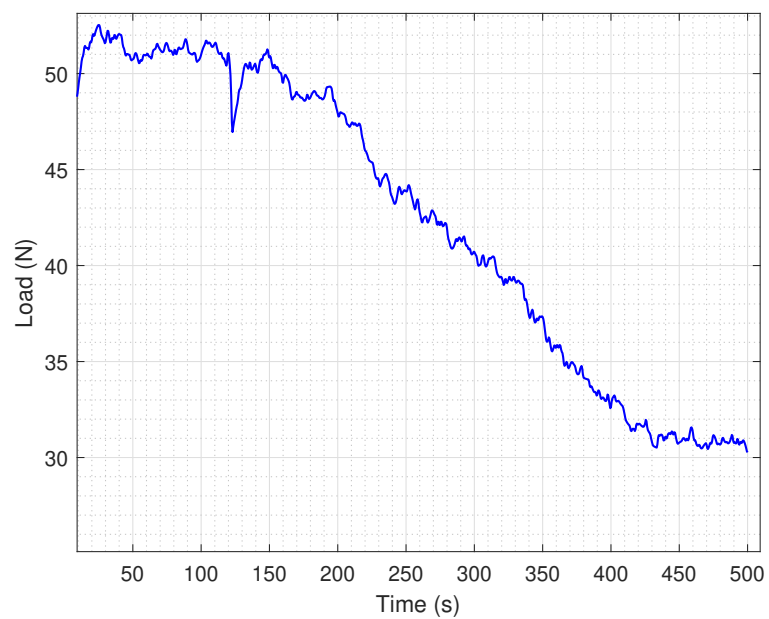


Figure 5.42 Decreasing load

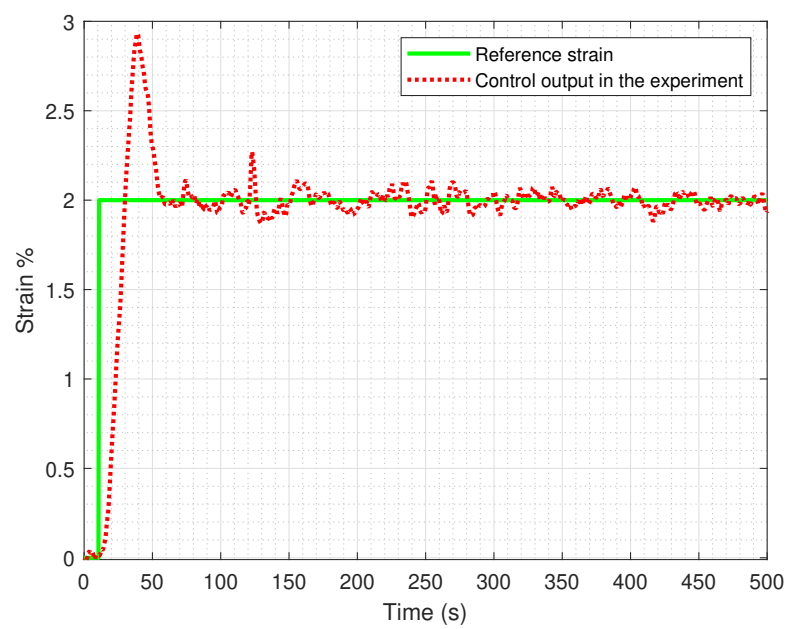
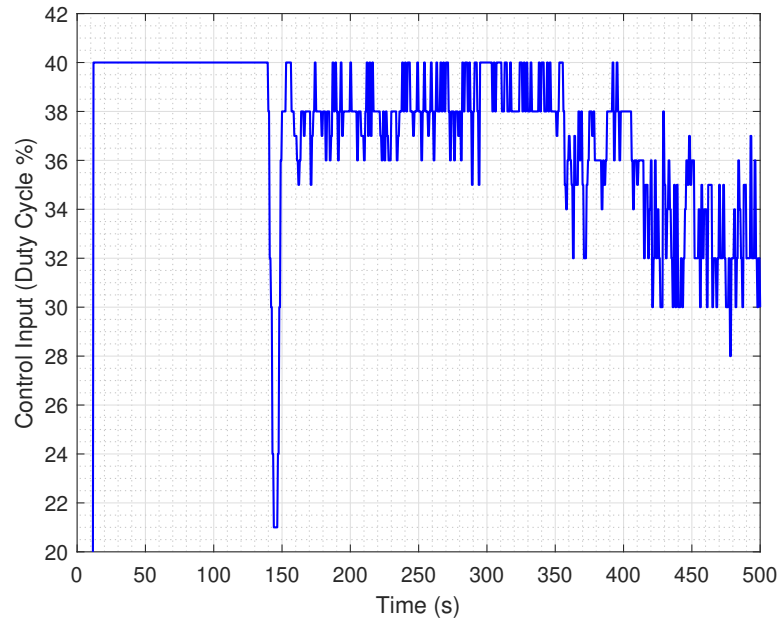
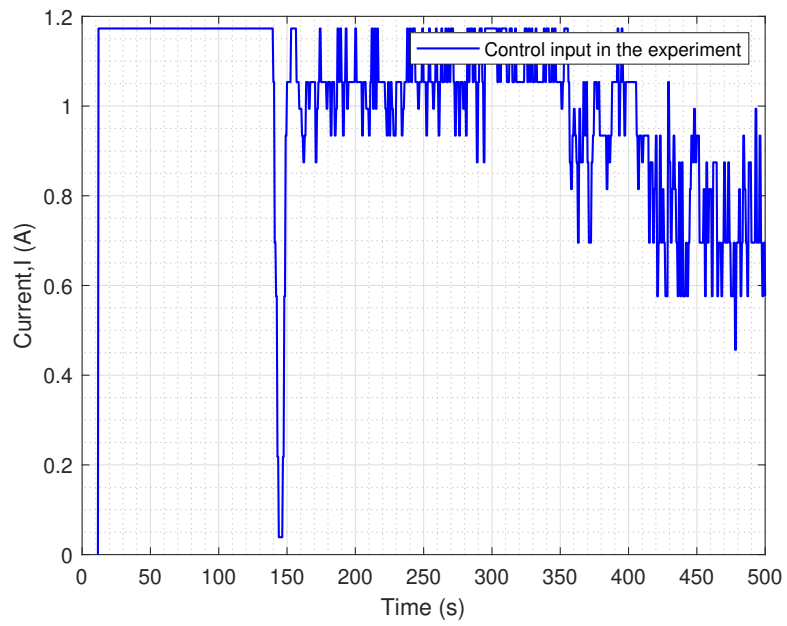


Figure 5.43 Reference control under decreasing in load figure 5.42



(a)



(b)

Figure 5.44 Control inputs for the control action in figure 5.43:(a) duty cycle % and (b) corresponding current

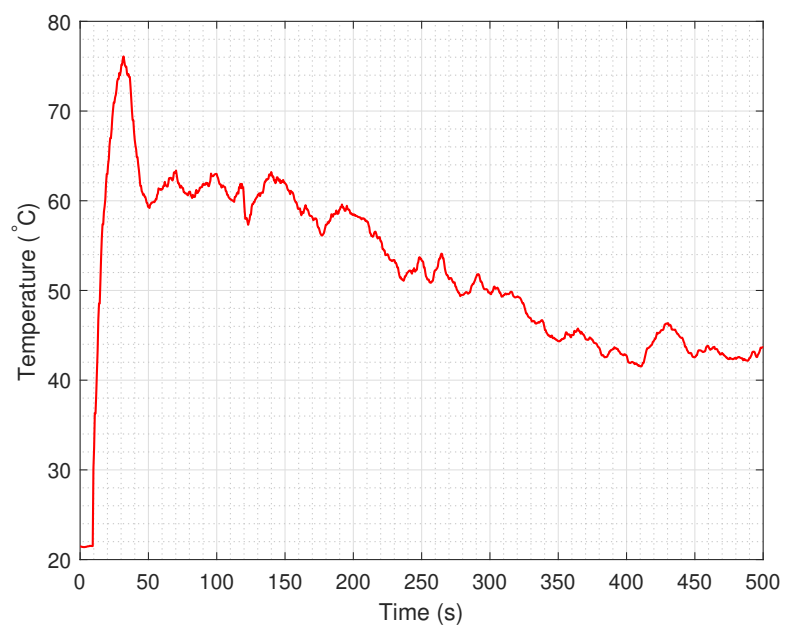


Figure 5.45 Temperature during decreasing load in figure 5.42

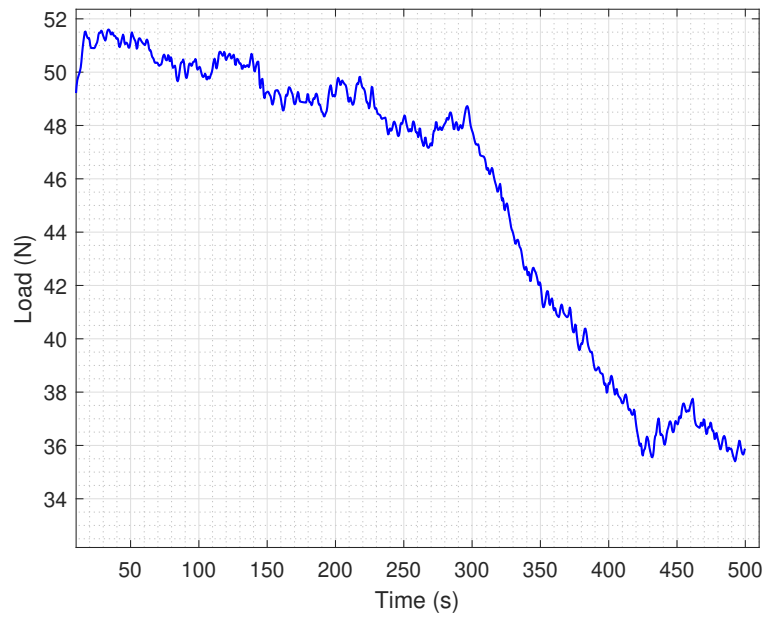


Figure 5.46 Decreasing load

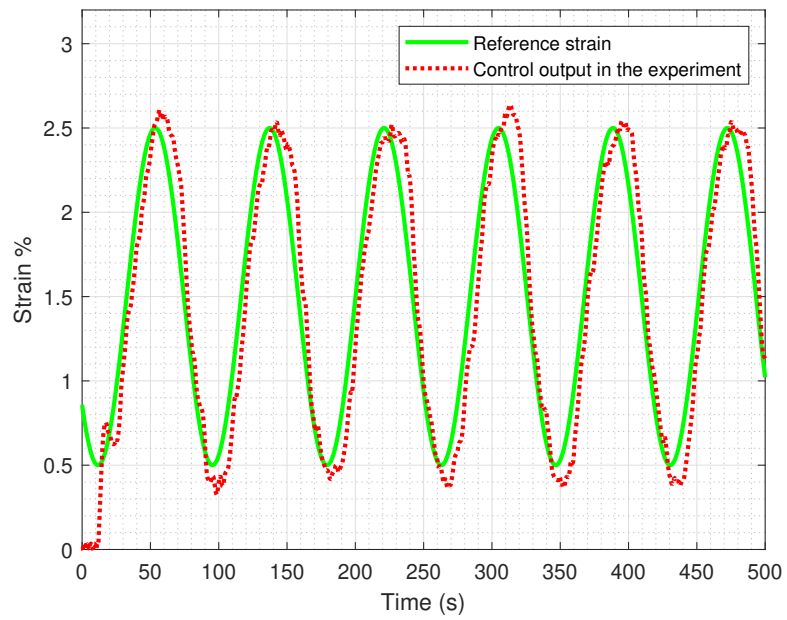
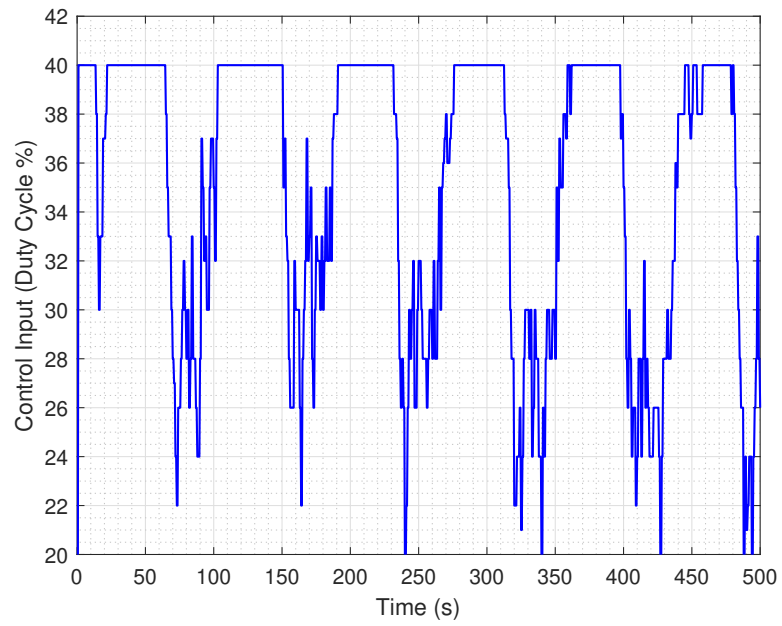
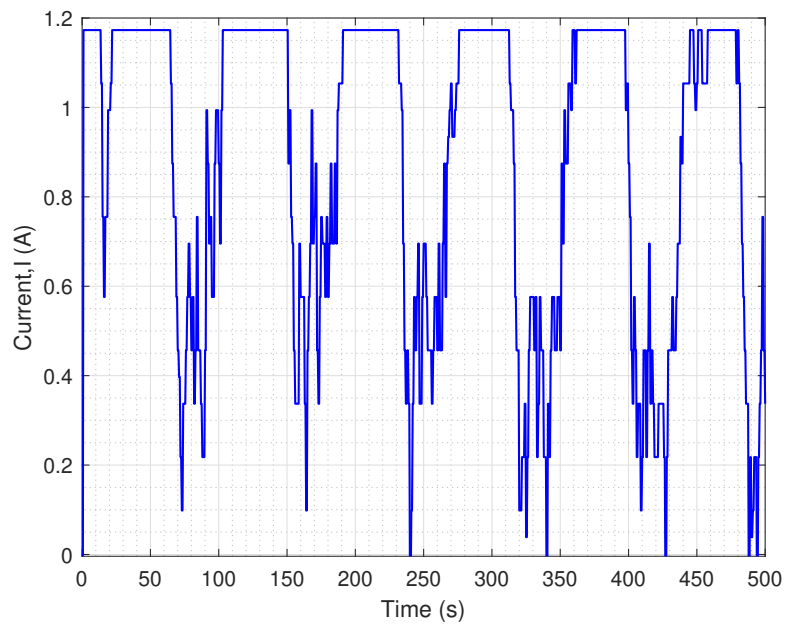


Figure 5.47 Reference control under decreasing load in figure 5.46



(a)



(b)

Figure 5.48 Control inputs for the control action in figure 5.47:(a) duty cycle % and (b) corresponding current

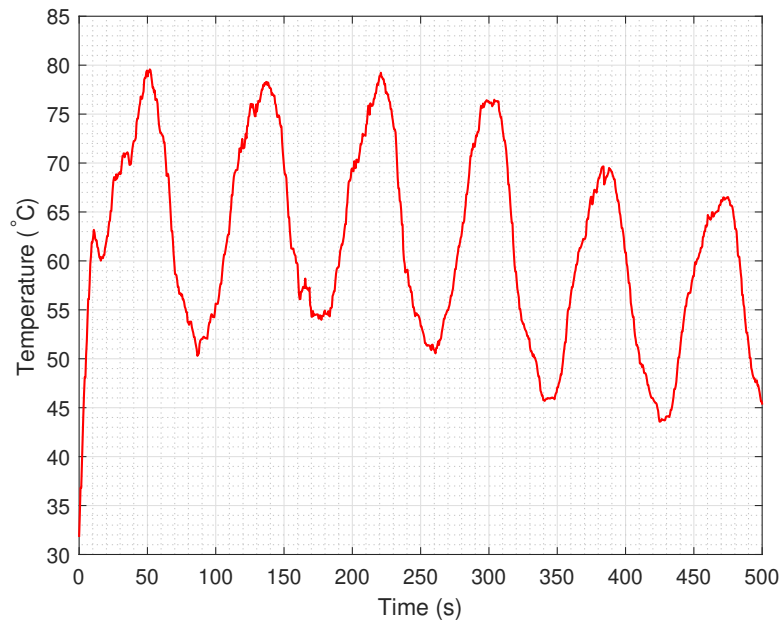


Figure 5.49 Temperature during decreasing load in figure 5.46

#### 5.4.1. Discussion

Tracking is tested for step reference signal of 2% strain having phase transition and for sine reference signal covering whole behaviour of the hysteresis. It can be concluded that the tracking does not go wrong in spite of variable loading. The controller is robust against this effect.

## **6. AN ACTUATOR DESIGN BY USING AN SMA WIRE: SPIRAL**

Shape memory alloy (SMA) wires are widely used within polymeric composite structures to create soft actuators [46, 63, 76, 80]. SMA wires generally exhibit small stroke in this kind of structures and this restricts the performance of actuators. In this study, a spiral design is suggested to increase the actuation stroke and for a two-way actuator. In most of actuator designs, pre-strain is given before connecting the wire to the structure in order to increase the bending in soft structures. An SMA wire can be stretched to approximately 3%-8% of its length without being damaged under load [103–106]. It is also possible to increase the strain by extending the length of the wire used. In this study, the structure provides actuation stroke by using only the wire of 189 cm, it does not need to give pre-strain or use longer wire to increase the strain. The spiral design provides an elastic property due to its twists, in addition, the TPU preferred for composite is an elastomer, it has a flexible structure. Therefore, actuation is provided by opening and closing instead of bending the structure. Besides, a two-way actuator is obtained since the design can store energy so that it can return to its pre-actuation state.

### **6.1. Design and Fabrication**

The length of the SMA wires used in this study is approximately 189 mm, of which 169 mm is embedded into the TPU structure. A length of 10 mm extends along the paddle at the flat end of the spiral and the remaining part of the length extends along the paddle at the incurved end of the spiral. These ends of the wire are connected to the copper wires (can be seen in figure 6.6) which send electrical current to the wire in the TPU structure. There will be some requirements when determining the wire location in the TPU structure. The SMA wire should be connected as far as possible from the neutral axis of the structure to provide bending in soft structures [83] and more actuation stroke and fast response. The SMA wire is heated to actuate. Hence, wearing of the structure under cycling actuation due to increase

and decrease of the temperature should be considered. Therefore, it is necessary for sufficient thickness to remain on the structure to prevent it sticking out, when connecting away from the neutral axis. This causes a kind of trade off. In this study, the appropriate location for the wire has been experimentally determined. The position where the wire provides actuation without sticking out is determined 0.675 mm away from the neutral axis.

In soft actuators [120], the SMA wire is generally embedded in any polymeric structure. In this study, the method is connecting. The TPU structure is formed with 3D printer and the wire is easily integrated. Therefore, alternatives are suggested to time-consuming and inconvenient processes such as molding and curing.

The tolerance given to the connection points. Some tolerance is added between the connection points in TPU structure and the wire. There will be a relative motion between TPU structure and SMA wire. However, it is shown that high stroke can be achieved during the motion of the spiral. Additionally, the structure can return to the pre-actuation state again. The structure cools down by convection while returning.

In this study, ‘spiral building method on two points’ is preferred for easy drawing in CAD program because each expanding semicircle arithmetically depends on the first one as given in the equation (31).

$$R_i = ir \quad (31)$$

The center coordinate,  $C_i(x,y,z)$ , of each circle has a simple rule on xy plane in equation (32), where  $C(x,y,z)$  is center of the first semicircle with the radius  $r$ . The values used for this study are shown in table 6.1.

$$\begin{aligned} \text{if } i \text{ is odd} \quad C_i &\equiv C(x, y, z) \\ \text{if } i \text{ is even} \quad C_i &\equiv C(r, y, z) \end{aligned} \quad (32)$$

A spiral body profile in CAD software is created by using two semicircles with radius  $r$  and  $R_1$  and a quarter sized circle with radius  $R_2$ . The tail of the quarter sized circle is kept flat

|          |            |
|----------|------------|
| $l$      | 56 mm      |
| $r$      | 8 mm       |
| $R_1=2r$ | 16 mm      |
| $R_2=3r$ | 24 mm      |
| $C$      | (0, 24, 0) |
| $C_1$    | (0, 24, 0) |
| $C_2$    | (8, 24, 0) |

Table 6.1 Dimensions and positions of the main profile of the spiral for drawing

on the horizontal position. This part of the design gets the connection with any movable component easier if the entire structure can be used as an actuator.

After the profile has been drawn as given in figure 6.1 in a CAD program (in this study, CATIA R20), the design is transferred to the 3D printer. 3D printer is paused at the middle of the printing process; the wire is integrated to the printed part of the structure as it can be seen in technical drawing in figure 6.2 and printed part of the structure in figure 6.3. Then, 3D printing is resumed.

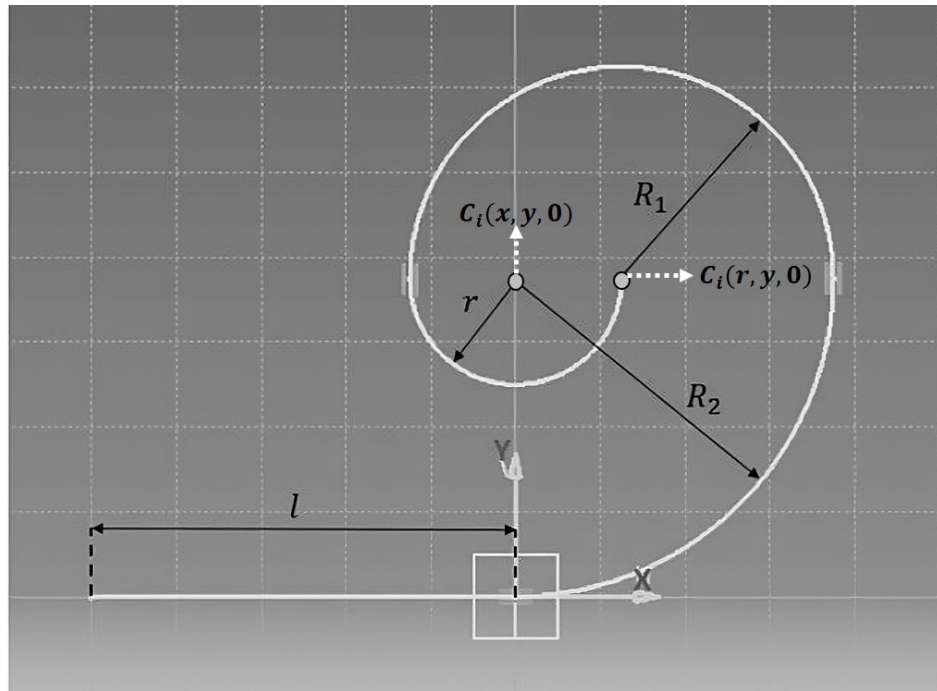


Figure 6.1 Main profile of an spiral for drawing in CAD (CATIA)

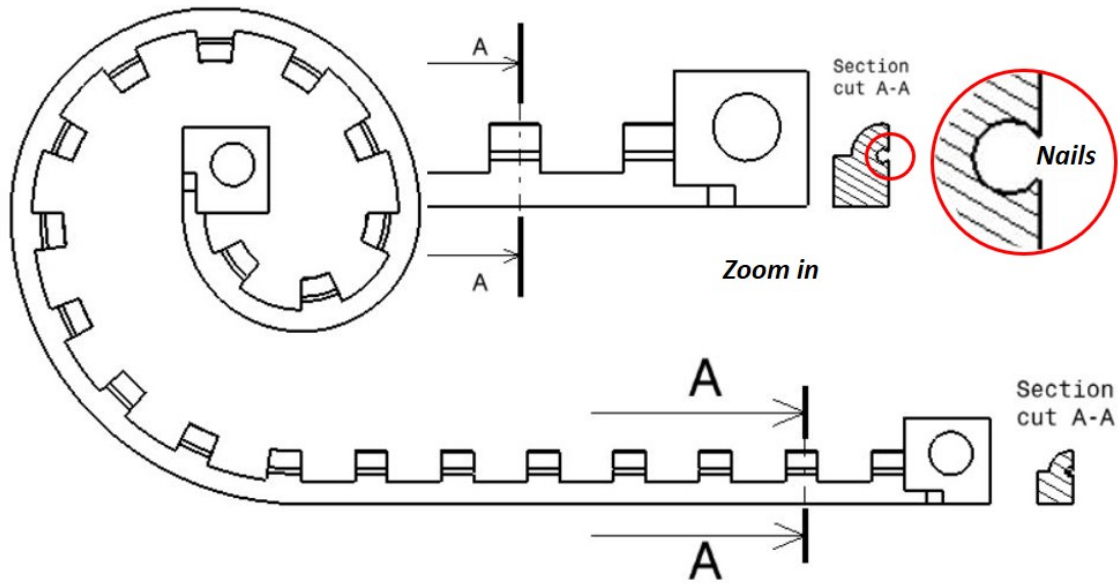


Figure 6.2 Pausing state and nails of a spiral for wire embedding

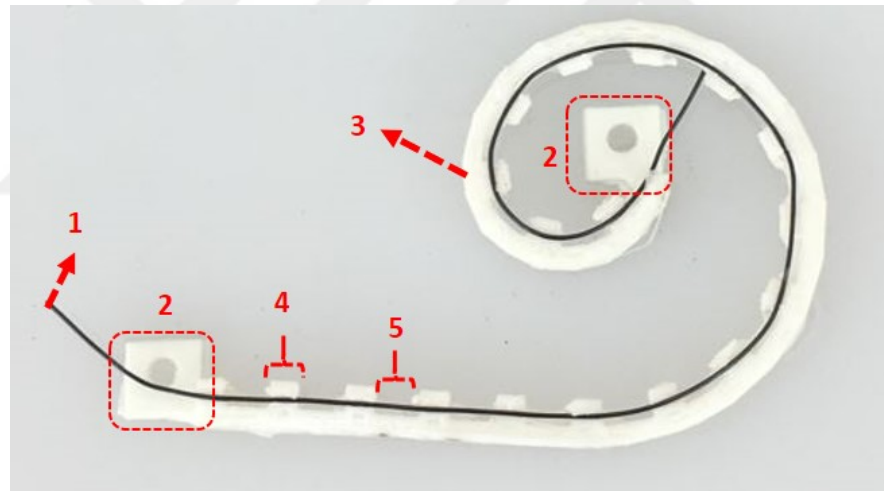


Figure 6.3 Printed part of a spiral structure during the aborting for the wire embedding. (1) SMA wire, (2) paddles for connection, (3) TPU body, (4) arch and (5) pocket

Interference fit is the ideal solution to avoid loss of force action and possible relative motion within TPU structure. However, there are two major drawbacks. Firstly, it is difficult to integrate the wire at high temperature. The building plate of the 3D printer can heat up to 70°C for TPU filament. The temperature at this degree is higher than the SMA wire temperature  $A_s$  ( $A_s=40^\circ C$ ). Hence, the wire starts to transform to the austenite phase. It becomes difficult to give the wire a spiral shape, because the wire stiffness is higher at this

phase. The other drawback is related to the printing procedure. It is possible to embed the wire into the TPU structure by pausing the printer. Firstly, there will be a slot in the TPU structure for the wire and the printer must be paused before closing the slot. After the slot starts to cover, in other words, after the printing passes the middle of the full printing procedure, when the TPU structure still lays on the xy plane on the printer plate, the printer is paused to embed the wire. The state of the TPU structure during pausing is important. Half of the structure should be printed and in fact, the progress of the printing should pass this position until almost the close of the slot. In that case, the structure has the nails on the both side of the holes as shown in figure 6.2 and these nails make the integration of the wire easier. When pausing, the nails are thin enough in order that the wire should be put down to the slot just by a little force. Also, they are thick and tall enough for the center of the slot to avoid the bounce back of the wire from the slot. Thus, after some trial and error to optimize, 0.15 mm tolerance in the radius is given to the slot to overcome these drawbacks SMA wire is used with 0.25 mm radius. Additionally, it is observed that the time needed to make the convenient nails occur for the wire integration is approximately two-thirds of the total printing time. An integrated example at that time is given in figure 6.3.

|          | $d_o$ (mm) | $d_c$ (mm) | $\alpha_{1o}$ (°) | $\alpha_{1c}$ (°) | $\alpha_{2o}$ (°) | $\alpha_{2c}$ (°) | $\alpha_{3o}$ (°) | $\alpha_{3c}$ (°) |
|----------|------------|------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Spiral 1 | 0          | 56         | -                 | -                 | -                 | -                 | -                 | -                 |
| Spiral 2 | 3          | 5          | 7.5               | 13                | 12                | 20                | 25                | 40                |
| Spiral 3 | 5          | 3          | 13                | 7.5               | 20                | 12                | 40                | 25                |
| Spiral 4 | 7          | 2          | 18                | 5                 | 28                | 6                 | 65                | 15                |

Table 6.2 Dimensions of the pattern on the spirals

## 6.2. Selection of The Optimal Spiral Design and Standardization

As mentioned previously, large stroke is important for the present implementation of SMA based actuators. Along with stroke, requirement actuation time should be controllable according to actuation reference. Especially, time of return back from the final actuation

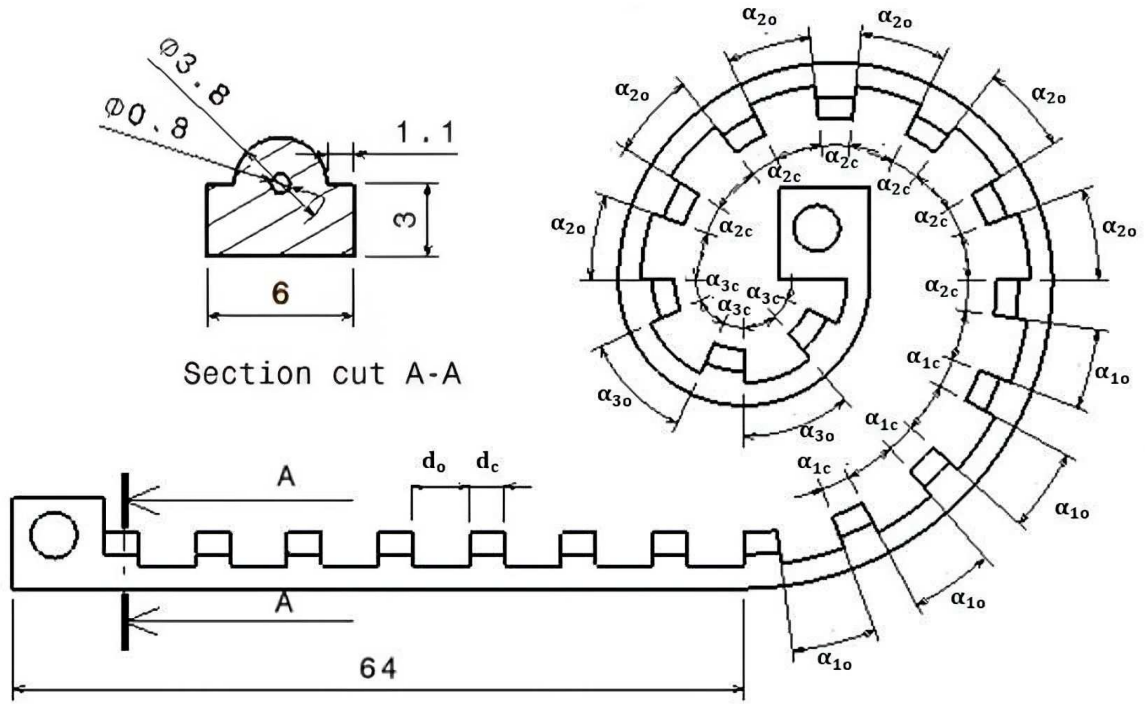


Figure 6.4 Common spiral profile for all designs (dimensions in mm)

position to the initial position is a known problem for the SMA based actuators. Cooling should be as fast as possible in order to start a new actuation cycle. The spiral actuator is cooled by the natural convection in this study compared to other cooling methods.

If the SMA wire completely remains inside the TPU structure, natural convection occurs only from the TPU structure surface. As to the TPU structure, it warms by conduction from the SMA wire. Considering the above some pockets were created on the composite structure to expose the wire to the ambient. Additionally, the neutral axis along the spiral structure shifts away from the wire due to the pockets and the motion capability of the spiral increases because of the reduced mass.

Four spirals have been designed to observe the effect of the natural convection on the cooling time, in other words, fast actuation response. The Spiral 1 is a completely closed design while the others have increasingly larger pockets. The four spirals are analyzed in this section

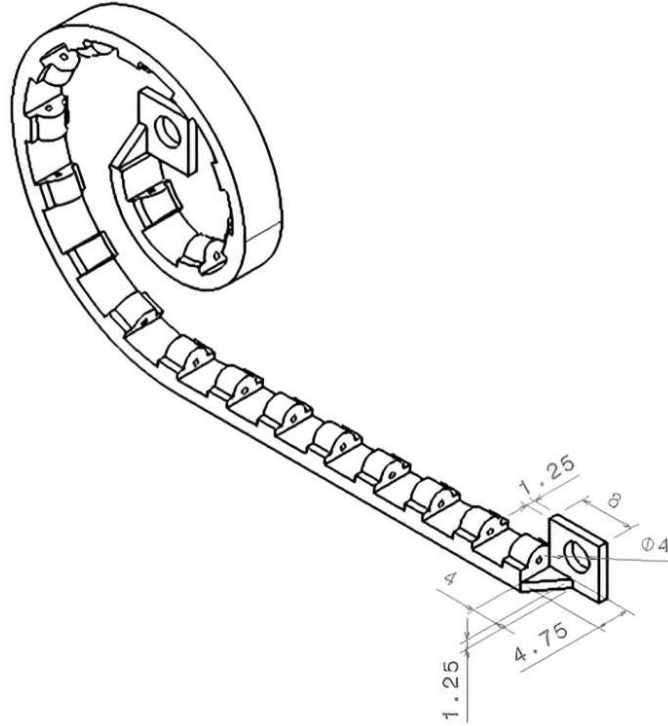


Figure 6.5 Common dimensions for paddles on isometric view of Spiral 3 (dimensions in mm)

6.2.3. in terms of their cooling time, i.e. actuation performance. Then, the Spiral 3 has been selected as explained in section 6.2.4. and section 6.2.5..

### 6.2.1. Design of The Spirals with Pockets

A common spiral profile is given in figure 6.4 for the mentioned four spiral designs. Changing dimensions of each spiral design are parametric in this figure. Arches and pockets on flat part of the spirals are represented by  $d_c$  and  $d_o$ , respectively. Arches and pockets on circular parts of the spirals are shown with  $\alpha_{ic}$  and  $\alpha_{io}$ , respectively where  $i$  represents three circles with radius  $r$ ,  $2r$  and  $3r$ . The same dimensions for every spiral are given in "Section cut A-A" in figure 6.4 and figure 6.5. Figure 6.5 also gives an isometric view for Spiral 3. The values characterizing four different spiral designs are listed in table 6.2.

The angles on the spiral are determined so as to be almost equal to the pattern on the flat part of the spiral. In other words, chords in front of the angles almost equal to pockets and arches on the flat part of the spiral as defined in equation (33) and equation (34).

$$r \sin \alpha_{1o} = R_1 \sin \alpha_{2o} = R_2 \sin \alpha_{3o} \approx d_o \quad (33)$$

$$r \sin \alpha_{1c} = R_1 \sin \alpha_{2c} = R_2 \sin \alpha_{3c} \approx d_c \quad (34)$$

Four spirals are given in figure 6.6 from fully closed design to the open.

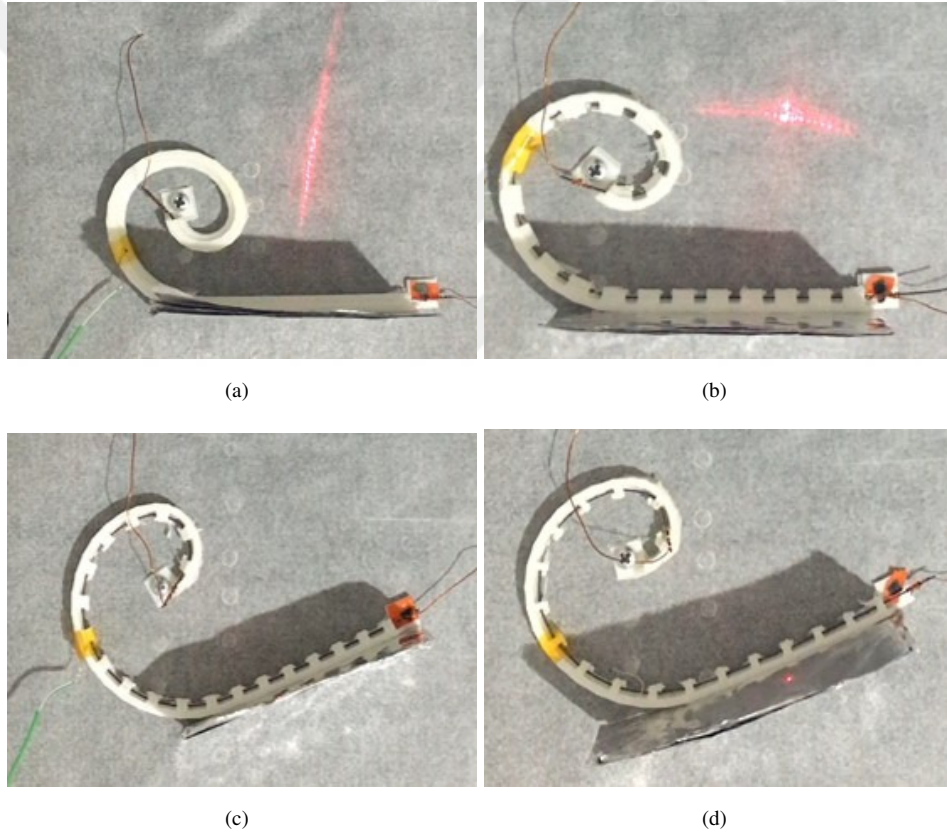


Figure 6.6 Four spiral designs: (a) Spiral 1 (b) Spiral 2 (c) Spiral 3 (d) Spiral 4

### 6.2.2. Experimental Setup

In this study, the paddle at the incurved end of the spiral is fixed to provide the actuation around this end. In other words, the movable part is the flat arm of the spiral.

When heated, the wire tries to return to its original flat shape. In this study, the wire is heated by Joule Heating. So, it is necessary to pass the current through the wire. The wire starts to change to the fully martensite phase in which it exhibits lower strength. Thus, the spiral can reach the initial position by means of the energy stored in TPU. Besides flexibility of the TPU, elastic effect of the spiral geometry also contributes to the motion. Finally, a two-way actuation opening during heating and closing during cooling can be observed by the spiral design.

The wire part sticking out from the flat arm of the spiral is connected to the current source in a way not to resist the motion while the current is given to heat the wire. Therefore, thin and light copper wires are winded around the ends of the SMA wire.

Components of the experimental setup are described in this section. This setup is used for all spiral design selection, repeatability of the spiral and control tests which are mentioned in next sections.

The incurved end of the spiral is fixed on the thin, holey metal panel. The panel is covered a smooth paper to decrease loss of motion capability that can be caused by the friction between spiral actuator and plate.

A laser displacement sensor (Panasonic HG-C 1100) is mounted on the plate. Its location is determined considering the opening-closing action range of the spiral actuator. In this study, the laser sensor is used for control application. The feedback signal is the two-directional linear displacement of the flat arm of the spiral in the application.

A dedicated printed circuit board (PCB) in figure 6.7 is designed. The electrical current passing through the SMA wire can be controlled by the circuit. The electronic circuit receives electrical current from the power supply using PWM signals according to the command sent by PC. Additionally, temperature data coming from the thermocouple, distance data coming from the laser sensor and the electrical current data passing through the wire are also collected by PCB.

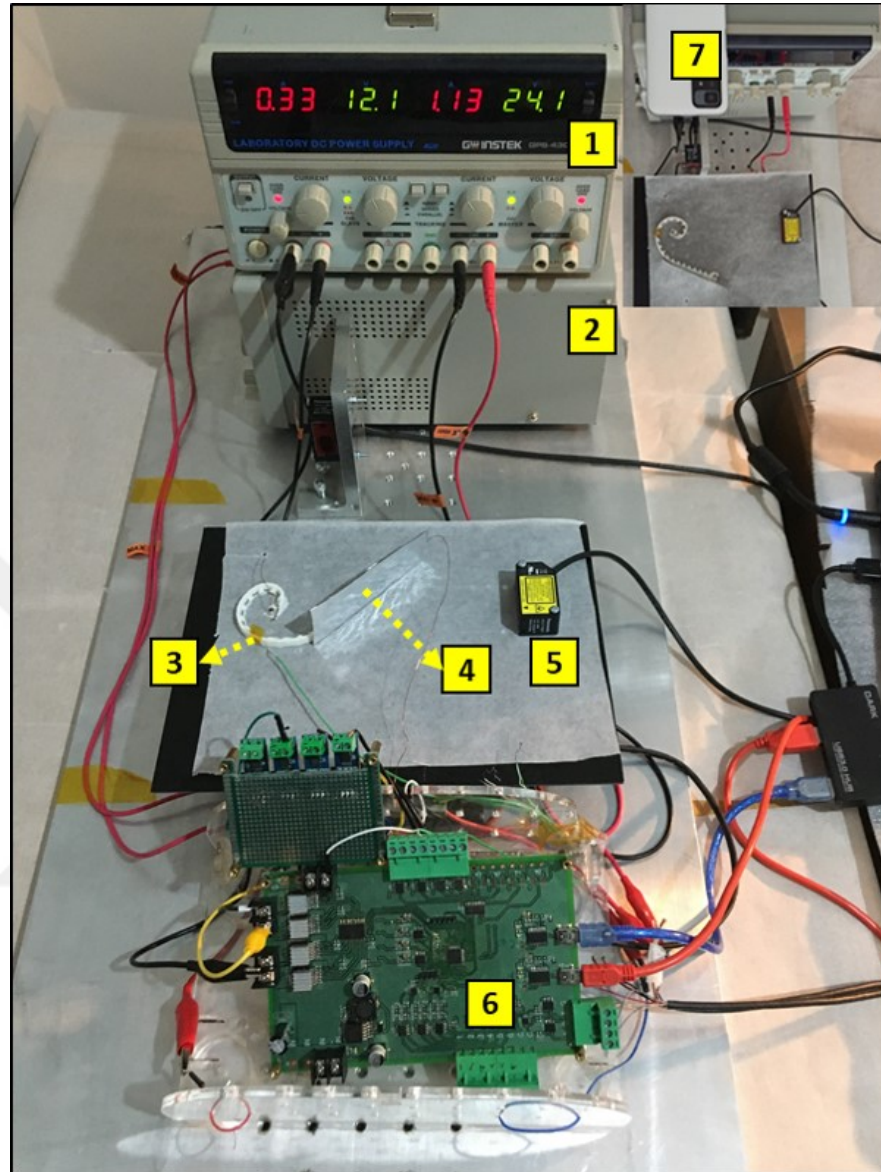


Figure 6.7 Experimental setup: (1 and 2) power supplies, (3) thermocouple with kapton tape on the spiral, (4) reflective surface for laser sensor, (5) laser displacement sensor, (6) electronic circuit, (7) camera positioned perpendicular to record the motion of the free end of the spiral

Finally, a K-type thermocouple is connected on the wire by a Kapton tape. In this way, the thermal isolation is provided against the interference of the measurement with the environment.

Two power supplies are used to supply the electrical circuit, the laser sensor and the SMA wire with the electrical current.

### **6.2.3. Determination of Heating/Cooling Paths and Response Times of The Spirals by Using Image Processing Method**

The actuation path of the free end of the spiral follows a planar curvilinear profile. In this section, cartesian components resulting curvilinear profile are created to determine the most convenient spiral. There are two criteria for the spiral selection: planar stroke (larger stroke is preferred) in both directions and actuation time. Indeed, if the cooling is only provided by natural convection, cooling time is dominant in actuation time compared with heating time. Therefore, the most ideal spiral shall be the one having the shortest cooling time.

Image processing method is used to see the paths of the free ends of the spirals. For this purpose, firstly, a camera perpendicular to the actuation plane is placed over the spiral to record the actuation. Then, video data are processed by Tracker [121] Video Analysis and Modeling Tool. This is a free software for image processing. Videos recording of the four spirals are loaded to Tracker. Tracker tracks the motion by using RGB codes. So, the free ends of the spirals are encoloured by using contrast colours as shown in figure 6.8 for better tracking performance. The origin of the axes is positioned on the mass point tracked by Tracker. The axis is rotated in order that the spiral path completely moves on positive directions. The directions are marked on figure 6.8. Also, an object with its length known has been taken into the video records. The length of the object is defined by Tracker as calibration stick in order to be a reference dimension for spiral motion. Number of the frames per step and frame rate are entered as 10 and 50/s respectively. Tracker can plot the motion at the same time when the image is processed. Open-close steps for Spiral 3 are given in figure 6.9 as an example of Tracker software operation.

All planar paths obtained by Tracker software are shown together in figure 6.10 for four spirals. Accordingly, Spiral 1 is quite poor in terms of the actuation stroke. Spiral 3 and Spiral 4 exhibit larger stroke. Hysteresis can be observed, especially during Spiral 3 activation, due to material properties of the SMA wire. Hysteresis in Spiral 4 is divided by cross passing at the part where the distances are around 36 mm in both x and y directions. This can be considered as a negative aspect about actuation properties of Spiral 4. Finally,

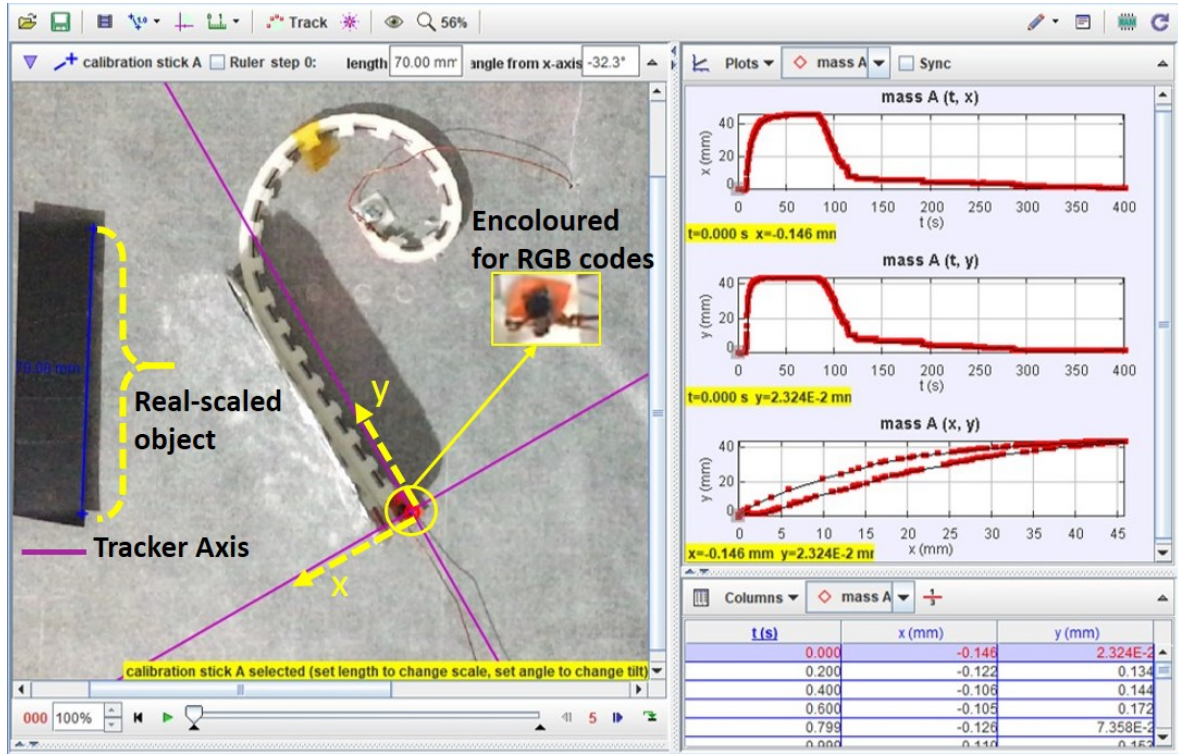


Figure 6.8 Specifications of the image processing operation in Tracker software

compared with Spiral 3, Spiral 4 has an improved stroke of 8 mm at x direction. Eventually, according to above considerations, selection of Spiral 3 as the optimal actuator is plausible.

The same amount of electrical current of 0.59 A, i.e. duty cycle of 30%, is passed through the SMA wire for all four spirals in the experiment. The constant electrical current is given to the wire at 20<sup>th</sup> second and cut off at 80<sup>th</sup> second as seen in figure 6.11. Frame number should be as low as as possible to reduce the total image processing time in Tracker software. Therefore, recording is started before 20<sup>th</sup> second but not synchronous with Matlab simulation start time. Video recording start times,  $V_s$  according to Matlab are noted in the first column of table 6.3. The graphs of the paths are separated for all four spirals in figure 6.12, figure 6.13, figure 6.14 and figure 6.15 and forward and backward actuation time data taken from Tracker are added to the graphs.

Forward actuation is defined as motion of the spiral from the instance,  $F_s$ , it starts to open to the instance it starts to remain stationary,  $F_f$ , under the electrical current. Thus, forward actuation time  $F_{at}$  can be defined between  $F_s$  and  $F_f$ .  $F_c t$  represents time interval in which

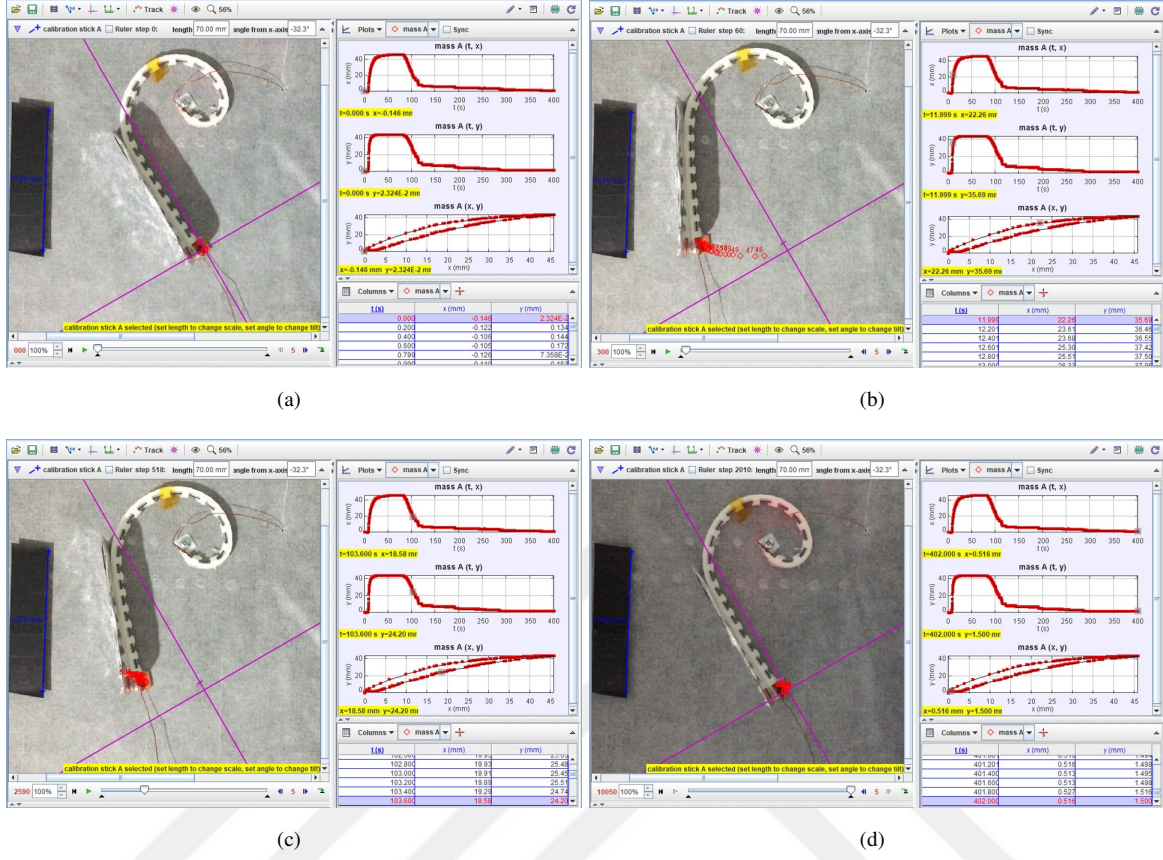


Figure 6.9 Sections during image processing operation in Tracker software: (a) Initial Position-Closed (b) Opening (c) Closing (d) Final Position-closed

motion at the free end of the spiral is not observed without cutting off the electrical current.  $I_{off}$  is defined as the instance when the electrical current is cut off in image processing. Cutting off occurs at  $80^{th}$  second in the simulation. After cutting off the electrical current, a delay time represented by  $B_{dt}$  is observed until starting backward actuation. Backward actuation is defined as motion of the spiral from the second it starts to close,  $B_s$ , to the second it returns to the initial position,  $B_f$ , under the electrical current. Thus, backward actuation time  $B_{at}$  can be defined between  $B_s$  and  $B_f$ .  $T_{at}$  gives total actuation time and is sum of the forward and backward actuation times.

Spiral 1 completes its actuation in shorter time comparing with Spiral 2 and 3, but this is due to fact that actuation stroke is quite short-range. It can be expected that cooling of Spiral 3 by natural convection needs to be faster than Spiral 2 because more wire surface is open to the

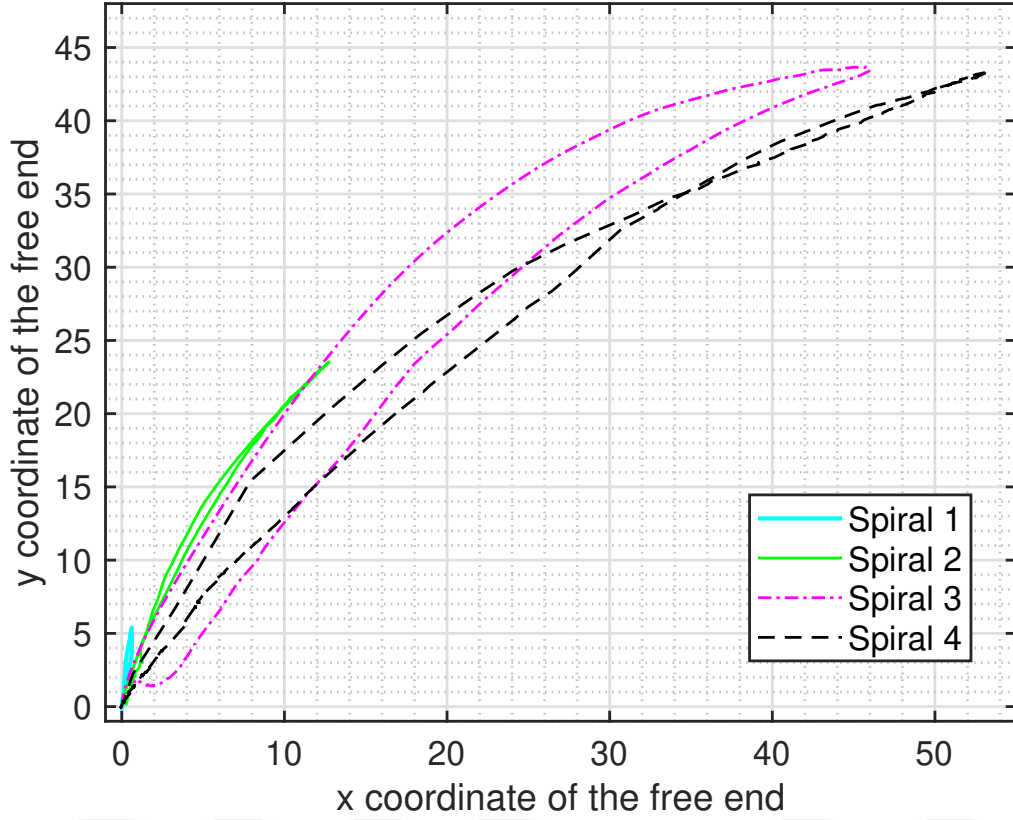


Figure 6.10 Planar distances for four spirals

ambient on Spiral 3, but cooling of Spiral 3 takes longer time. However, it can be seen that actuation stroke distance of Spiral 3 is much longer compared to Spiral 2. Actually, there exists a compromise between actuation stroke and actuation time for spiral designs. Hence, it is necessary to determine a metric to decide about which spiral is optimal as an actuator. For this, the distance between  $(0, 0)$ , the origin point where actuation starts and  $(x, y)$ , the final point where any spiral actuator reaches is defined as maximum constant distance,  $D_{max}$ , and is calculated by equation (35). Eventually,  $R_{dt}$  is defined as a ratio of maximum constant distance to total actuation time and is given with equation (36). Total actuation performance increases with increase of  $R_{dt}$ . Also,  $R_{dt}$  is separated to two parts as  $R_{dtF}$  and  $R_{dtB}$  for forward and backward actuation respectively to observe individually their effects on the total actuation. Equation (37) and equation (38) give  $R_{dtF}$  and  $R_{dtB}$  respectively.

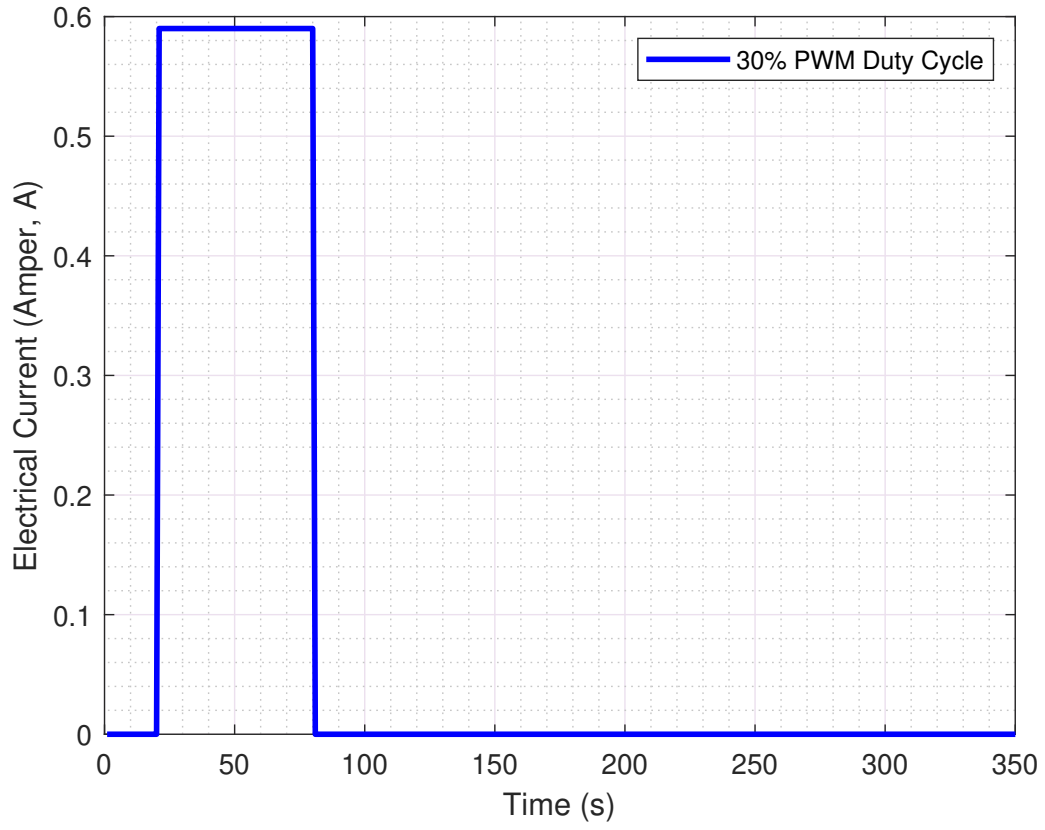


Figure 6.11 Electrical current

$$D_{max} = \sqrt{x^2 + y^2} \quad (35)$$

$$R_{dt} = D_{max}/T_{at} \quad (36)$$

$$R_{dtF} = D_{max}/F_{at} \quad (37)$$

$$R_{dtB} = D_{max}/B_{at} \quad (38)$$

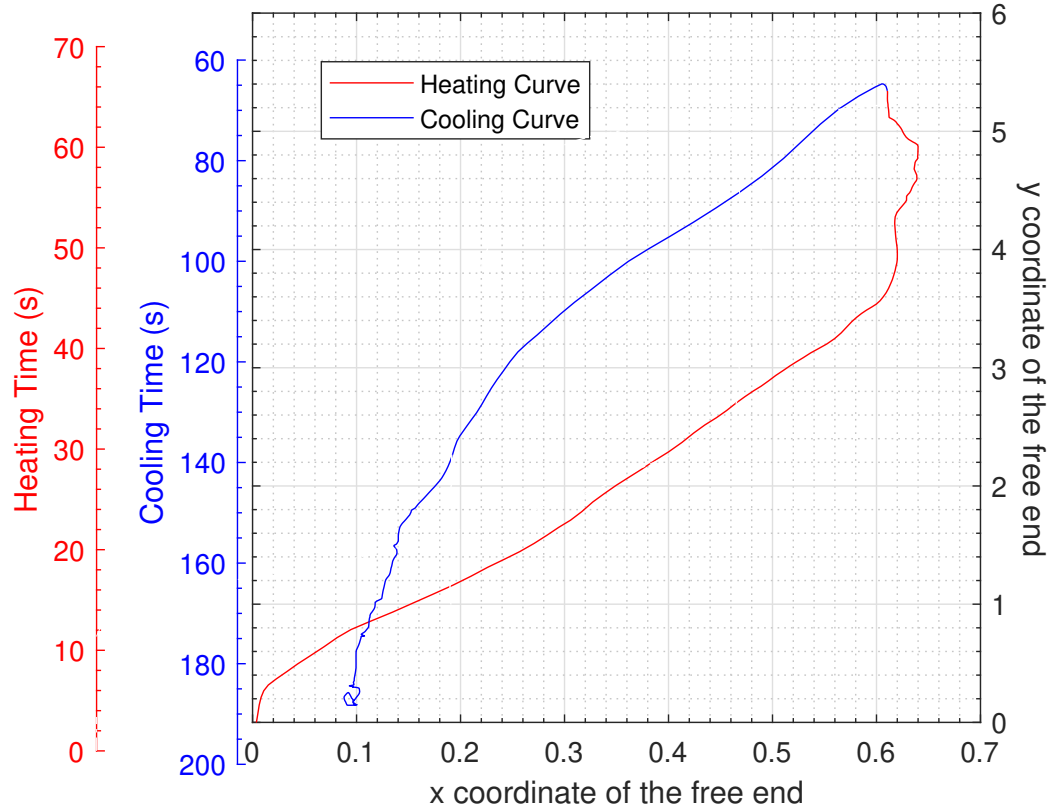


Figure 6.12 Planar actuation distance and actuation time for Spiral 1

All start and finish instances and time ranges are given in table 6.3 and maximum constant distance parameter and distance-time ratios mentioned are given in table 6.4.

|          | $V_s$<br>(-th s) | $F_s$<br>(-th s) | $F_f$<br>(-th s) | $F_{at}$<br>(s) | $F_{ct}$<br>(s) | $I_{off}$<br>(-th s) | $B_{dt}$<br>(s) | $B_s$<br>(-th s) | $B_f$<br>(-th s) | $B_{at}$<br>(s) | $T_{at}$<br>(s) |
|----------|------------------|------------------|------------------|-----------------|-----------------|----------------------|-----------------|------------------|------------------|-----------------|-----------------|
| Spiral 1 | 6.4              | 13.6             | 34               | 20.4            | 39.6            | 73.6                 | 6               | 79.6             | 138.8            | 59.2            | 79.6            |
| Spiral 2 | 7.6              | 12.4             | 67.2             | 54.8            | 5.2             | 72.4                 | 9.6             | 82               | 305              | 223             | 277.8           |
| Spiral 3 | 11.6             | 8.4              | 45.6             | 37.2            | 22.8            | 68.4                 | 10              | 78.4             | 374.4            | 296             | 333.2           |
| Spiral 4 | 8.8              | 11.2             | 17.6             | 6.4             | 53.6            | 71.2                 | 10              | 81.2             | 343.2            | 262             | 268.4           |

Table 6.3 Actuation times for four spirals

$B_{dt}$  is the same for both Spiral 3 and Spiral 4. Similarly,  $B_{dt}$  takes shorter time of 0.4 s than Spiral 3 and Spiral 4.  $B_{dt}$  for Spiral 2 is just 0.4 second shorter.  $B_{dt}$  for Spiral 1 is 4s faster.

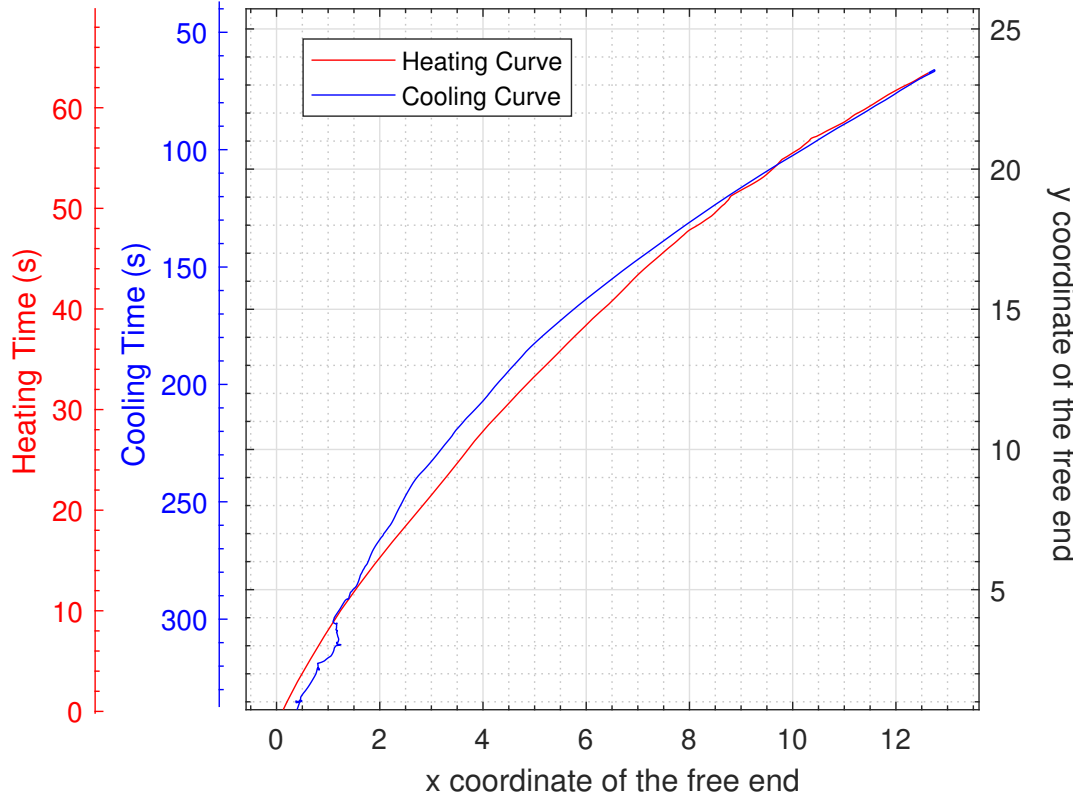


Figure 6.13 Planar actuation distance and actuation time for Spiral 2

It should be considered here that relative motion of the wire in the spiral structure is more restricted due to fully closed design.

$R_{dtB}$  exhibits similarity with  $R_{dt}$  as can be seen in figure 6.16. It means that  $R_{dtB}$  dominates the total actuation when comparing  $R_{dtF}$  part of the actuation. It can be seen that cooling is more important part of the total actuation to reduce the total actuation time and use of additional cooling systems can be come to mind while making this kind of designs.

Spiral 4 has the highest performance in terms of  $R_{dt}$ , in other words, considering the range of stroke and the total actuation time together. However, the wire sticks out in a short time after a several operation due to the arches which their width are decreased. After a while, as it can be seen in figure 6.17 the spiral structure is misshaped by deformed arches and length of the wire parts unconnected with the arches, because the long wire parts outside of the arches

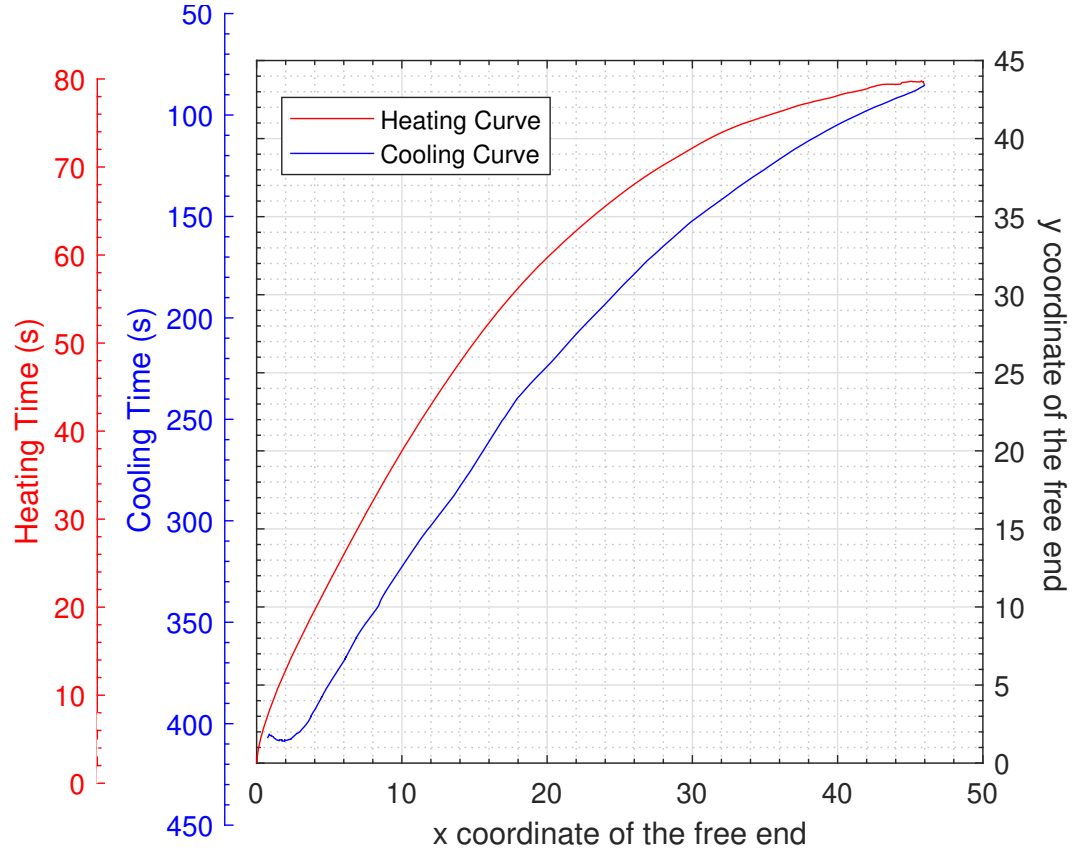


Figure 6.14 Planar actuation distance and actuation time for Spiral 3

hang and get wavy. Therefore, Spiral 3 is taken into consideration to see it can be optimal or not to use as an actuator. Thus, Spiral 3 and Spiral 4 are compared in terms of their actuation performance to make final decision.

Performance can be understood by increase in rate of  $R_{dt}$  in 6.16. The slope is 0.03 mm/s between Spiral 2 and Spiral 1 and increases to 0.09 mm/s between Spiral 3 and Spiral 2. Increase in the slope between Spiral 4 and Spiral 3 decreasingly becomes 0.07 mm/s. The superiority of Spiral 4 to Spiral 3 is not as major as the superiority of Spiral 3 to Spiral 2 and Spiral 1 in terms of actuation distance-actuation time performance. This can also be seen in figure 6.16. Also, it can be seen in figure 6.18 that the difference between performances of Spiral 3 and Spiral 4 is not as large as being between Spiral 3 and Spiral 1-Spiral 2.

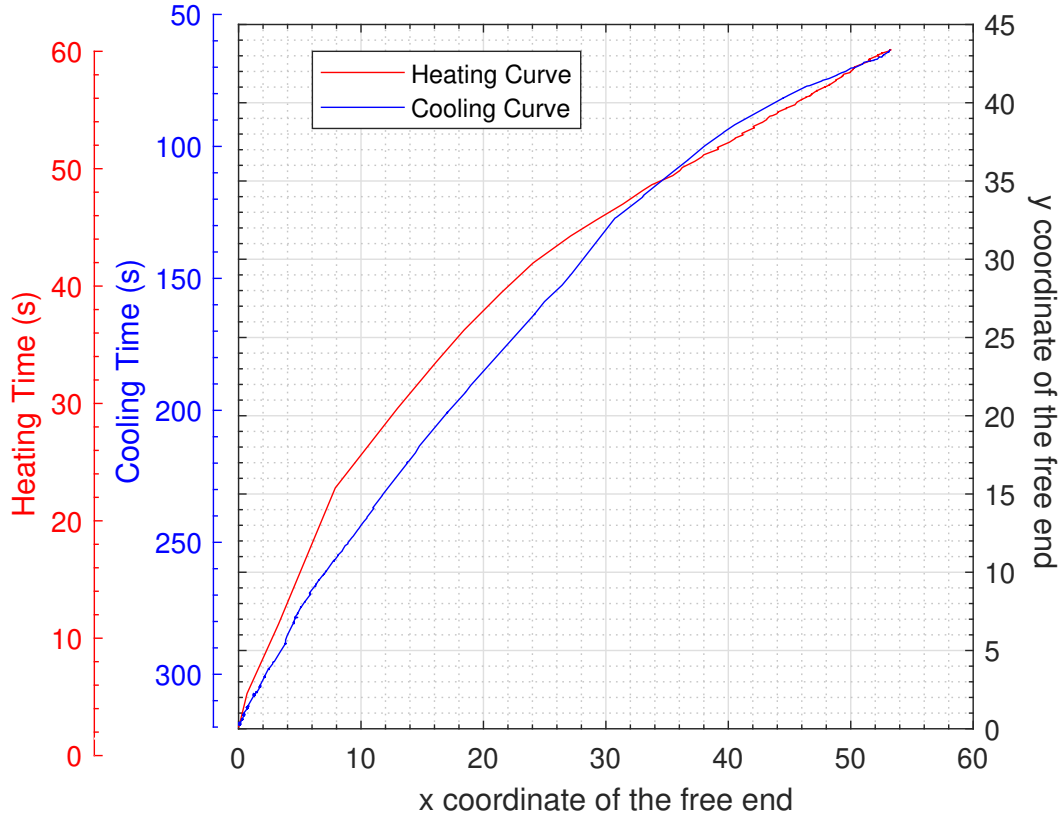


Figure 6.15 Planar actuation distance and actuation time for Spiral 4

Consequently, Spiral 3 is selected as an actuator which will be used for repeatability test, control and actuation application in next sections.

#### 6.2.4. Repeatability

Phase transition temperatures ( $A_s$ ,  $A_f$ ,  $M_s$  and  $M_f$  are austenite start, austenite finish, martensite start, martensite finish temperatures and the wire temperature, respectively) obtained from a characterization procedure for the SMA wire are given in table 6.5. The wire electrical resistance is measured as  $3.1\Omega$  using a multimeter. Thus, the wire is heated over  $A_f$  to reach fully austenite phase with a current of  $0.68A$  from ambient temperature at  $23^\circ C$  to  $120^\circ C$  by using the experimental setup in figure 6.7. PWM current signals controlled by the electronic circuit are sent into the wire. As a conclusion, two-way actuation test has

|          | $D_{max}$<br>(mm) | $R_{dtF}$<br>(mm/s) | $R_{dtB}$<br>(mm/s) | $R_{dt}$<br>(mm/s) |
|----------|-------------------|---------------------|---------------------|--------------------|
| Spiral 1 | 5.44              | 0.27                | 0.09                | 0.07               |
| Spiral 2 | 26.74             | 0.49                | 0.12                | 0.10               |
| Spiral 3 | 63.31             | 1.70                | 0.21                | 0.19               |
| Spiral 4 | 69.34             | 10.83               | 0.26                | 0.26               |

Table 6.4 Maximum constant actuation distances and time ratios for four spirals

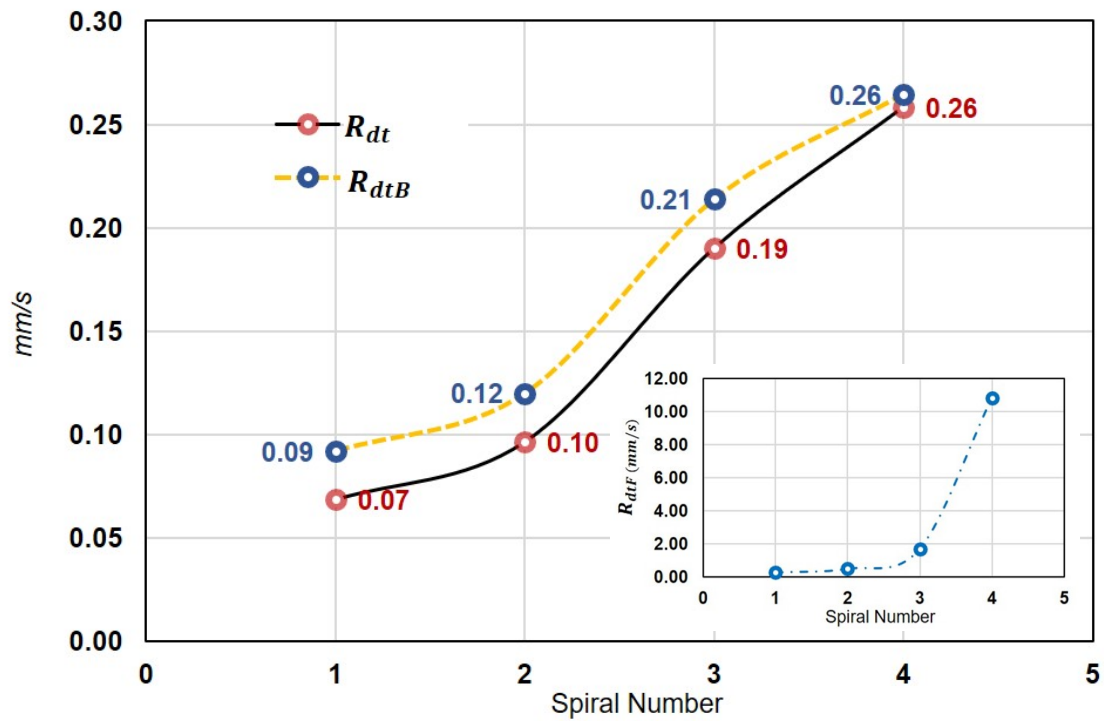


Figure 6.16 Maximum constant distance-actuation time ratios for four spirals

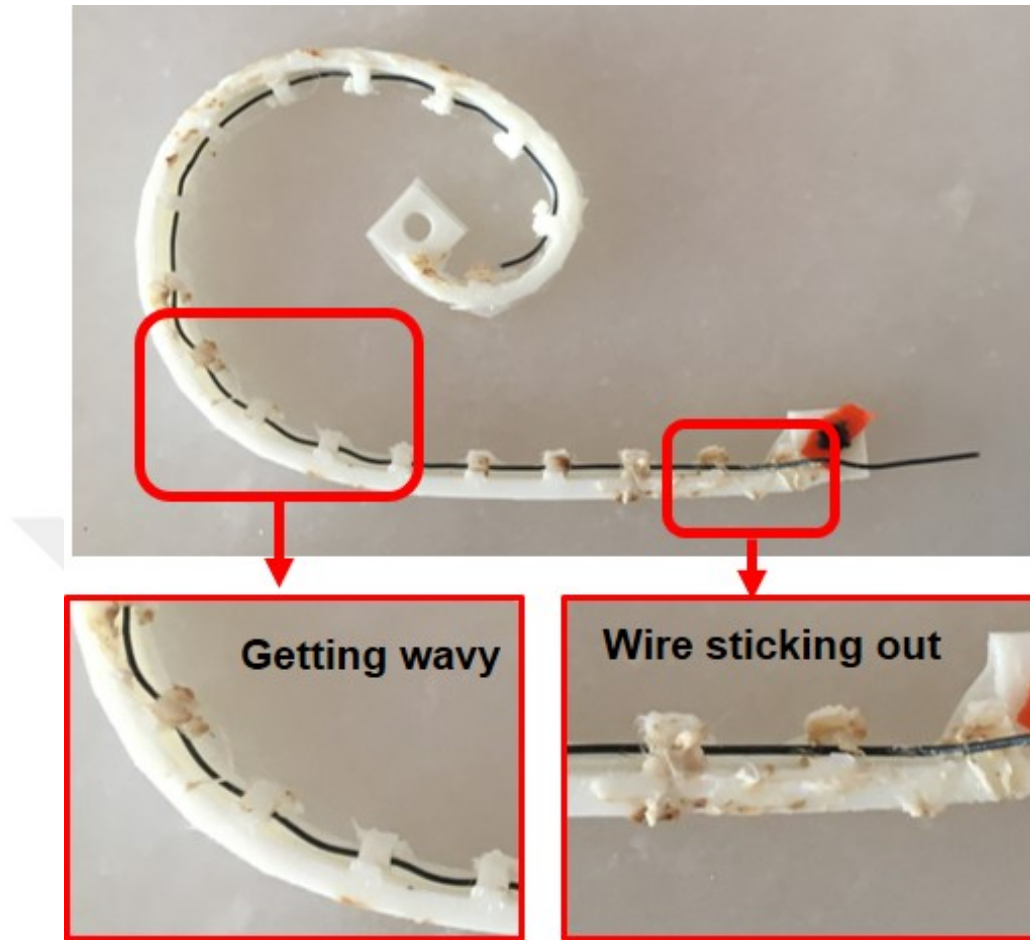


Figure 6.17 Deformations in Spiral 4

been carried out for 50 cycles; accordingly, spiral design is observed to be repeatable (in figure 6.19). Also, it is shown that the stroke can be increased from 1-2.5 cm strokes in some studies [1,2] to 5 cm (in figure 6.20) by using the same experimental setup again. The stroke is measured at the free end of the spiral; the spiral opens when heated and the linear displacement is measured by the laser displacement sensor while the reflective surface bonded on the free end of the spiral travels far away the laser displacement sensor.

| $A_s$ ( $^{\circ}C$ ) | $A_f$ ( $^{\circ}C$ ) | $M_s$ ( $^{\circ}C$ ) | $M_f$ ( $^{\circ}C$ ) |
|-----------------------|-----------------------|-----------------------|-----------------------|
| 40                    | 58                    | 45                    | 32                    |

Table 6.5 Phase Transition Temperatures

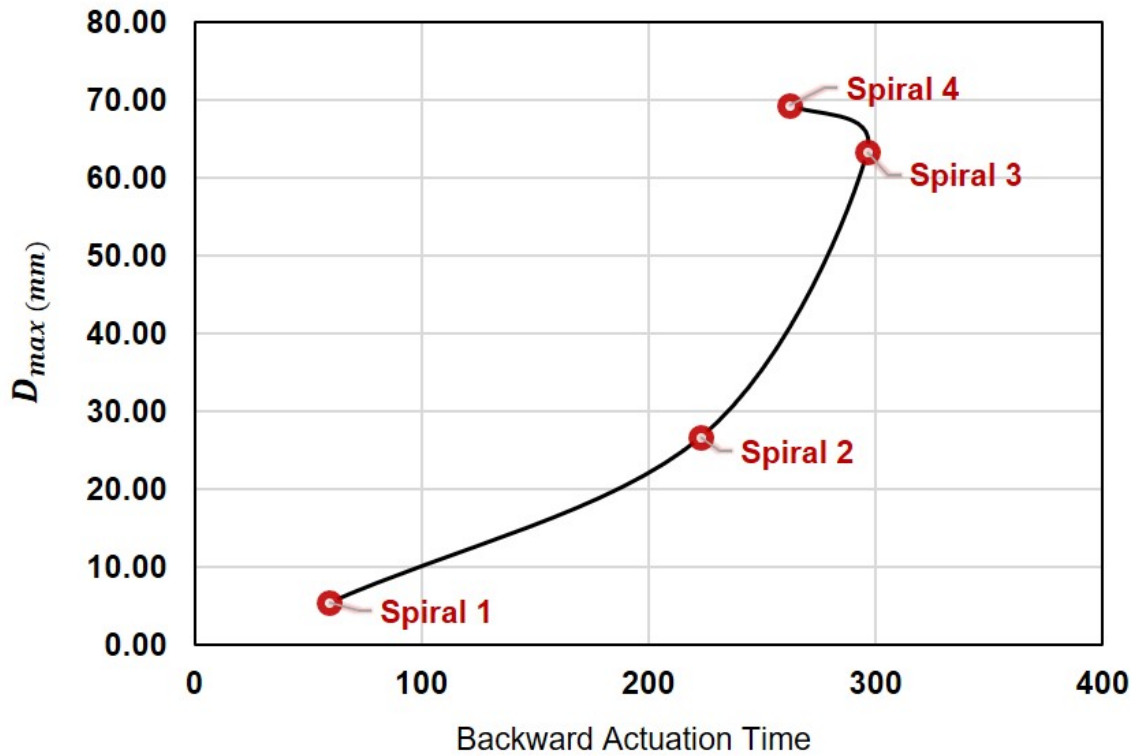


Figure 6.18 Maximum constant distance vs backward actuation time for four spirals

#### 6.2.5. Determining of Current Constraint for Spiral 3

Actuation stroke can be increased by higher electrical current to a certain extent. However, it is expected from the spiral actuator that it achieves actuation in high repeatability without loss of integrity. Therefore, electrical current should be constrained to operate the actuator safely and in optimal performance. Distance data in xy-plane was collected to determine the current constraint for Spiral 3. Duty cycle is raised with steps of 1%. Currents given by the electronic circuit to Spiral 3 were applied for 60 seconds and shown in figure 6.21. Also, currents corresponding to the duty cycle can be read in figure 6.21. Temperatures of Spiral 3 are measured as given in figure 6.22 for heating from the ambient temperature and cooling to the ambient temperature again. Difference between temperatures in the beginning is due to changing ambient temperatures during test and the measurements are completed close to the ambient temperature.

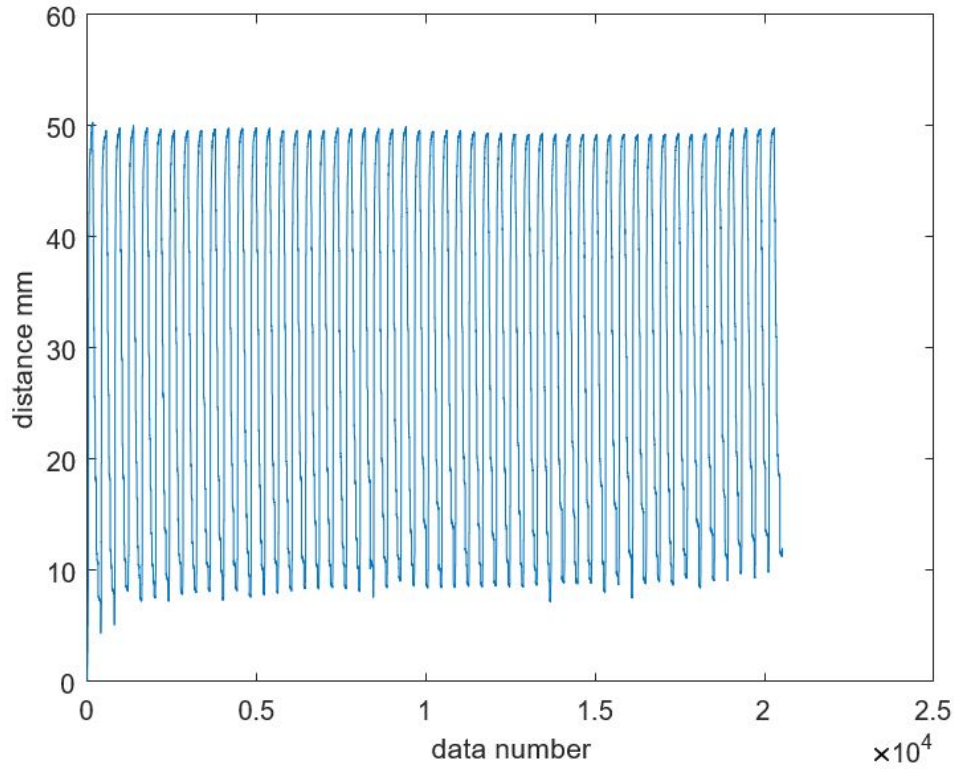


Figure 6.19 Total cycles for repeatability test

Figure 6.23 shows the both planar distances obtained from Tracker software and actuation time together during full actuation under different electrical currents for Spiral 3. The planar distances obtained from figure 6.23 are given in figure 6.24. Then, figure 6.24 is separated like in figure 6.25 to see the positions under different currents. According to this, firstly, it can be observed that hysteresis and opening in both x directions and y increases with increasing electrical current. There is a minor reduction in opening in x direction over 590mA. Actuation responses in 660mA and 720mA start to settle. It can be seen in figure 6.25 that temperatures reached by currents over 590 mA damage the spiral structure by melting TPU layer. Eventually, the current given to the wire was restricted to 590mA for the spiral actuator considering the observed damage and a minor difference between performances.

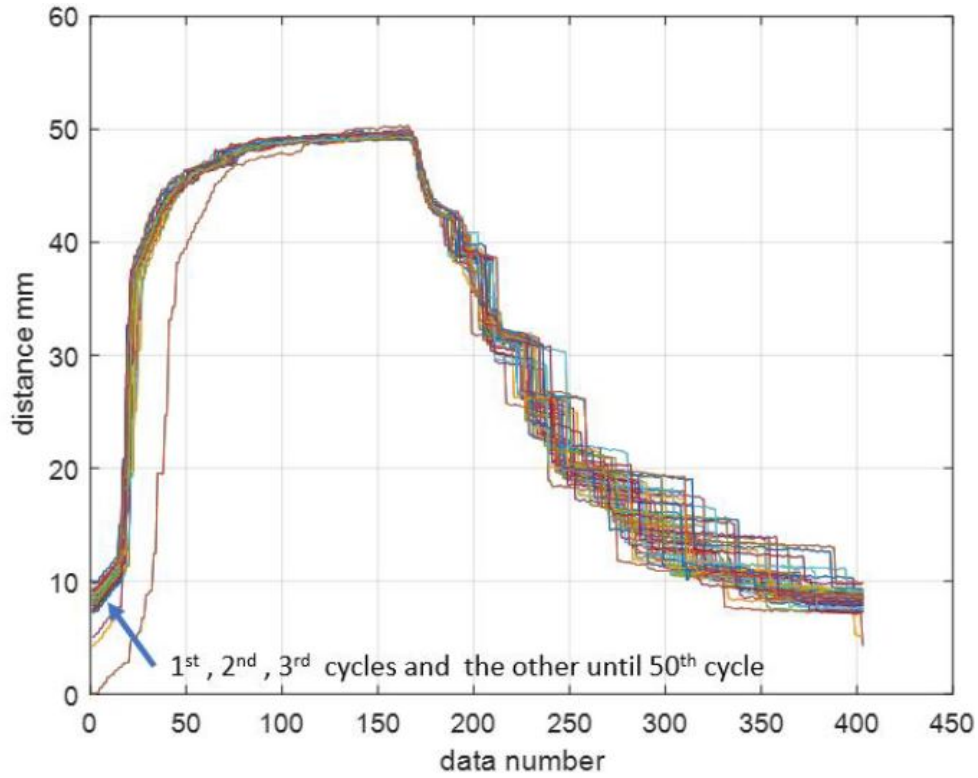


Figure 6.20 Superimpose of repeatability test cycles

### 6.3. PID Control For The Spiral Actuator

The PID gains for the controller were tuned so as to give the best tracking performance. According to this, proportional gain,  $K_P$ , integral gain,  $K_I$  and derivative gain,  $K_D$  were experimentally selected as 1, 0.2 and 0.85, respectively. Feedback is the linear distance in x direction measured by the laser distance sensor. The control output was limited by 30% duty cycle to prevent any damage on the spiral. Also, actuation distances in reference signals are restricted approximately to 20mm for safe control action. Therefore, the expected amount of electrical current passing through the wire is about 320 mA (26% duty cycle) and can also be seen in figure 6.25.

Firstly, a triangular reference signal in figure 6.27 is given to the system. The electronic circuit starts to feed an effective current over 20% duty cycle. Thus, for this reference signal, control input starts to load around  $10^{th}$  second. Heating and system output response are also effective around  $50^{th}$  second. The tracking starts about the  $60^{th}$  second at 4mm distance.

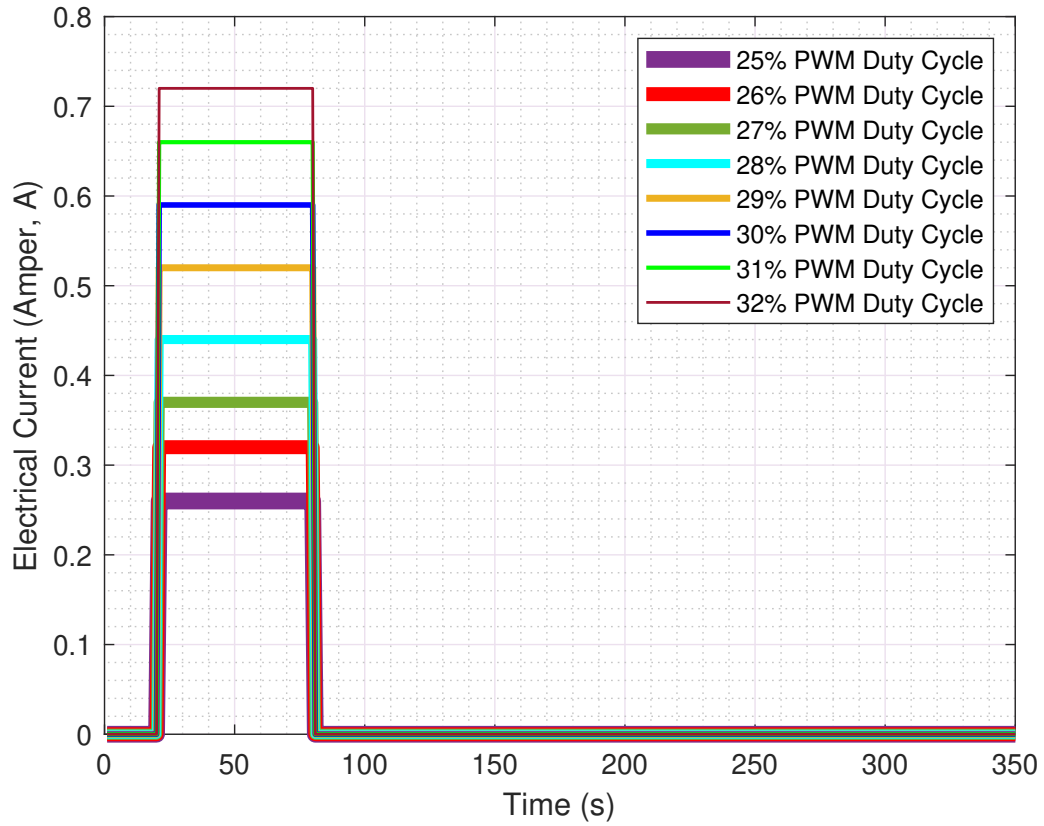


Figure 6.21 Duty cycles and corresponding currents

While the tracking continues, overshoots are observed between 130-220 s. The temperature raises from  $36^{\circ}\text{C}$  to  $40^{\circ}\text{C}$  at the same interval in figure 6.28(c). According to 6.5, As is 40. Here, it should be remembered that the characterization operation has been carried out under 3.5kg loading. So, phase transition temperatures were shifted to higher values. In other words, it can be expected that the phase transition temperatures without loading are lower. Additionally, the temperature is measured on the TPU structure. So, considering elapsed time for the conduction between the wire and TPU material and the loss of heat due to convection on the open surface pattern on Spiral 3, it is predicted that the actual temperature of the wire is higher with a couple of degrees in the mentioned interval. Consequently, it is noticed that the wire is in the beginning of the phase transition from martensite to austenite in that interval, which is the range where the overshoots are observed. In other words, the phase transition can cause sudden and large changing of distance. While the closing approaches

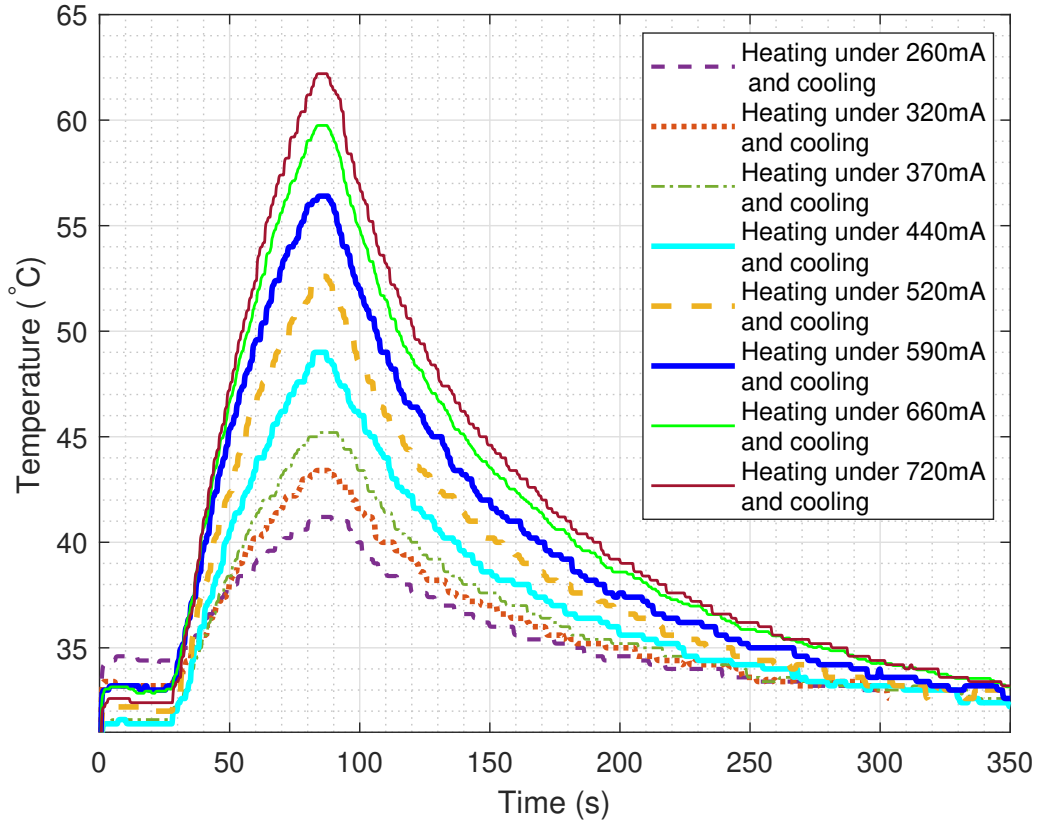


Figure 6.22 Composite structure temperatures under increasing current for Spiral 3

around the initial position, after  $400^{th}$  second, a fast decrease is observed in control input as can be seen in figure 6.28(a),(b). In spite of this, the error increases in tracking. There can be two explanations for this. First of them, complete returning to the ambient temperature relatively takes a long time as can be understood in figure 6.28(c). Secondly, spiral has some residuals due to flexibility of TPU.

The same delay explained for figure 6.27 is observed for figure 6.29 as well. Fast increase demand in the distance causes overshoots at  $100^{th}$ ,  $280^{th}$  and between  $420^{th}$  and  $440^{th}$ , and also, fast decrease demand causes undershoot at  $210^{th}$  as can be seen in figure 6.29. Besides, the tracking error increases with fast decrease demand to the distance close to the initial position due to cool slowly as can be observed after  $320^{th}$  second. As it is in the previous explanation, tracking error increases after  $445^{th}$  second in the initial position demand of the

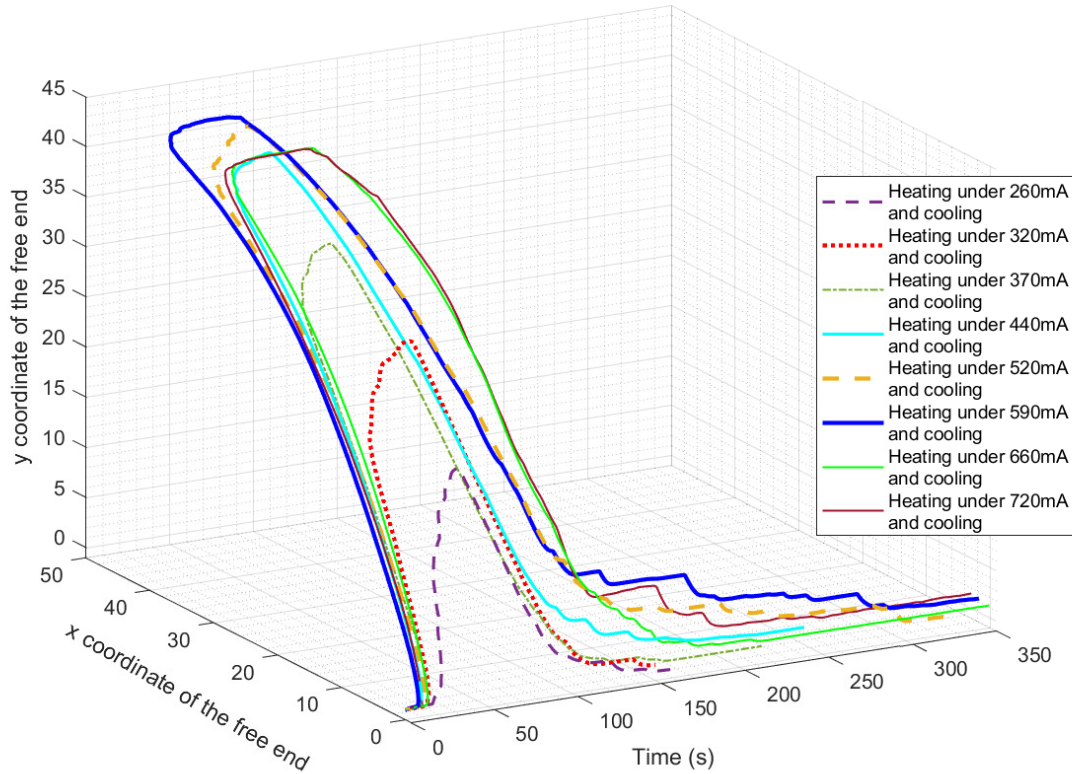


Figure 6.23 Planar distances and actuation times under changing current for Spiral 3

reference signal due to fast distance decrease demand, slow cooling and residuals. The control input and the temperature can be seen in figure 6.30

The reference signals in figure 6.31, figure 6.33 and figure 6.35 are formed with the steps divided by two respectively in the same experiment time. Here, there are some common observations. Magnitudes of overshoots and undershoots occurring in changing reference demands decreases a little with decreasing steps. On the other hand, zero error tracking can not be observed fast and long time due to decreasing waiting time in each step. Additionally, for good tracking, fast action of the controller can be ascertained from the oscillations becoming frequent control inputs given in figure 6.32(a),(b), figure 6.34(a),(b) and figure 6.36(a),(b). Also, the temperatures for all references proceeds in the similar range in figure 6.32(c), figure 6.34(c) and figure 6.36(c).

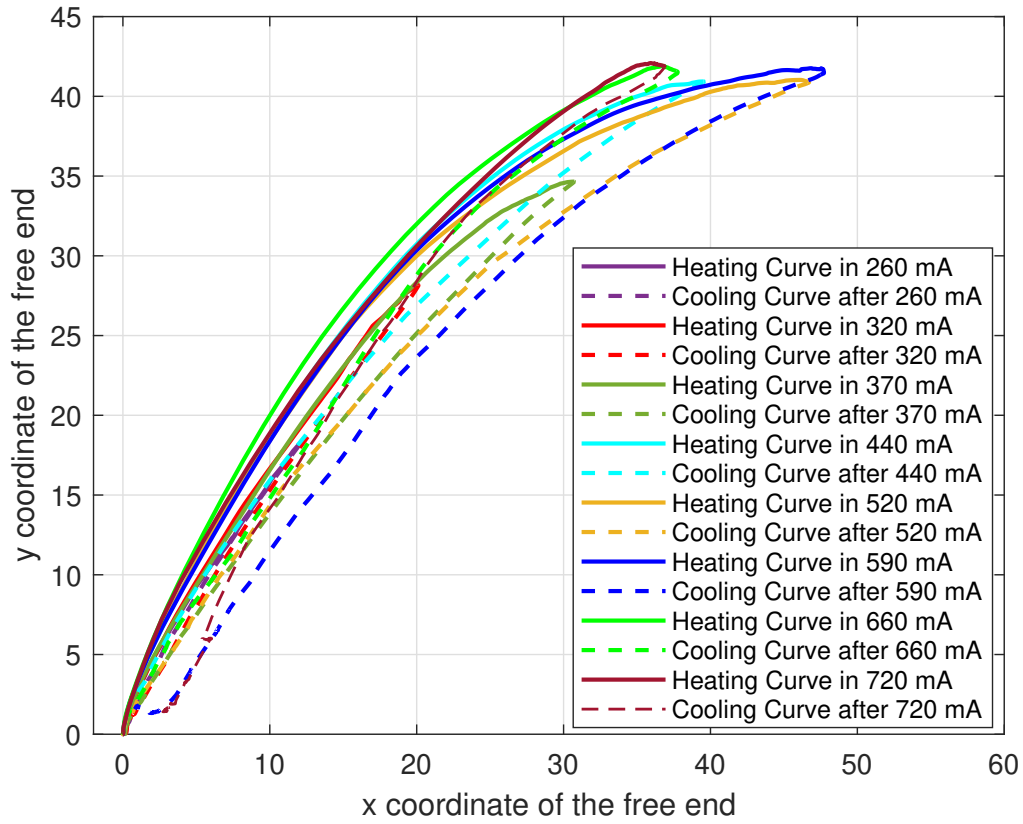


Figure 6.24 Planar distances under changing current for Spiral 3

It seems that the tracking error around the initial position during cooling can be decreased by decreasing distance demand and increasing waiting time. The reference signal in figure 6.37 is created. Distance is changed with steps of 1mm and it is desired that the spiral waits at the same position during 100 seconds. The views zoomed are put in figure 6.38 to observe the tracking clearly. According to this, with minor oscillations, good tracking can be seen even under returning demand of 6mm where residuals exist. Long heating and waiting time provide to measure little higher temperatures towards 42 degrees seen in figure 6.39(c).

Finally, a chirp reference signal in figure 6.40 is created to observe the control tracking performance under different frequencies and continuous passing instead of the stepped. Temperature rises in the beginning because of fast change of the continuous sine signal, although the reference signal demands lower distance of 10 mm. The input current increases to about 0.4 as can be seen in figure 6.41(b). Thus, the temperature reaches about 45degrees

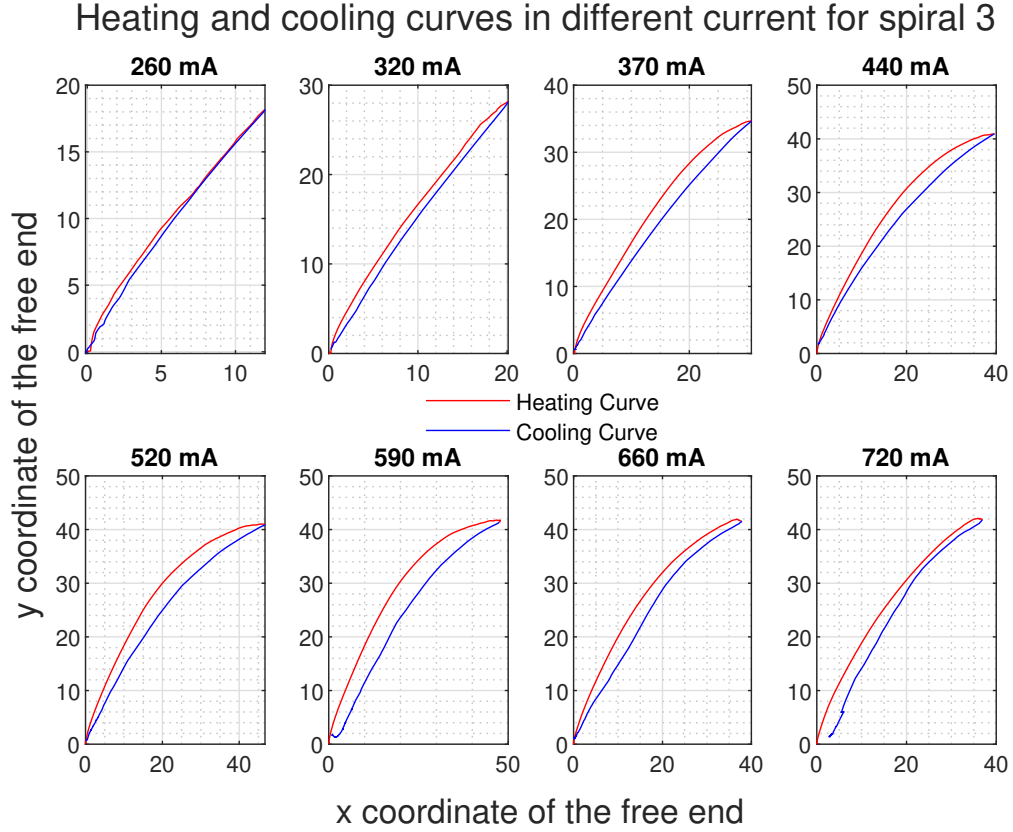


Figure 6.25 Separated planar distances under changing current for Spiral 3

as can be seen in figure 6.41(c). Change in the temperature starts to lessen with increasing frequency and the temperature stays on 45degrees. Nevertheless, tracking is provided. Therefore, change in the electrical current supplying the wire can be achieved setting the spiraling motion.

#### 6.4. Application: Spiral 3 as An Actuator

In this section, we present an actuator design based on dual usage of Spiral 3. The objective is to achieve object picking and lifting. The incurved ends of the spirals are positioned so as to be parallel to each other and are fixed. The fixed ends and the free ends are wrapped with the light and thin copper wires so as not to impede the motion of the actuators. Unwrapped ends of the copper wires connect to the electronic circuit. Two thin and wide sandpapers are attached to the free ends of the spirals for a stronger hold. The actuation is given in

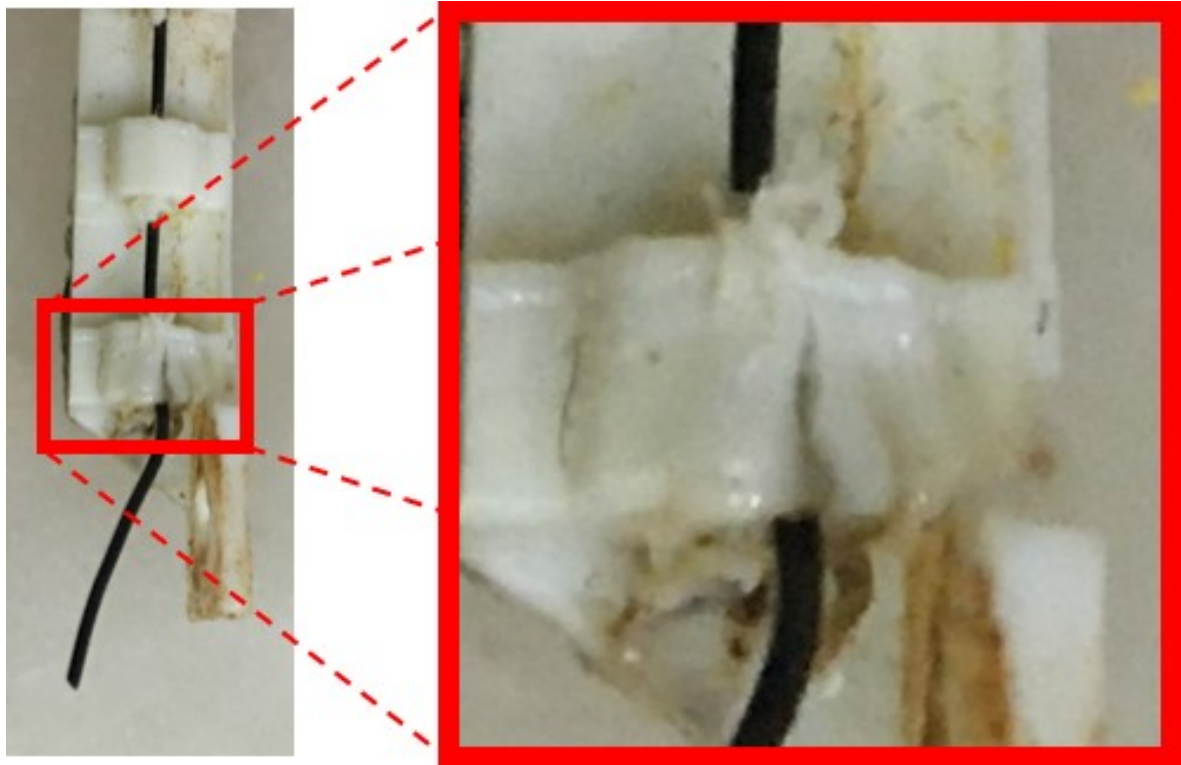


Figure 6.26 Damage over 590mA current

figure 6.42 from initial position (a) to final position (f) with all stages. Both two spirals are supplied with 0.59 A (i.e. 30% duty cycle) electrical current during closing. Holding of the object between the spiral arms can be observed in figure 6.42(b). Then, lifting of the object is successful as can be seen in figure 6.42(c). The object starts to hang down towards the platform after cutting off the electrical current in figure 6.42(d). The arms are separated from the object, while convectional cooling lasts in figure 6.42(e) and finally, actuator returns back the initial position in figure 6.42(f).

Tracker software is used again to see the amount of the lifting. According to figure 6.43, the lifting can be seen to reach to about 6.5mm. There is an important point that needs to be emphasized in that application. In these kind of actuators, after holding an object, the platform on which the actuators are fixed is lifted up and the object is transferred to another position. This has been already achieved, in addition to this, as an advantage and a contribution to the literature, the weight of 6.5 gr can automatically be lifted up to 6.5mm by the spirals in this application.

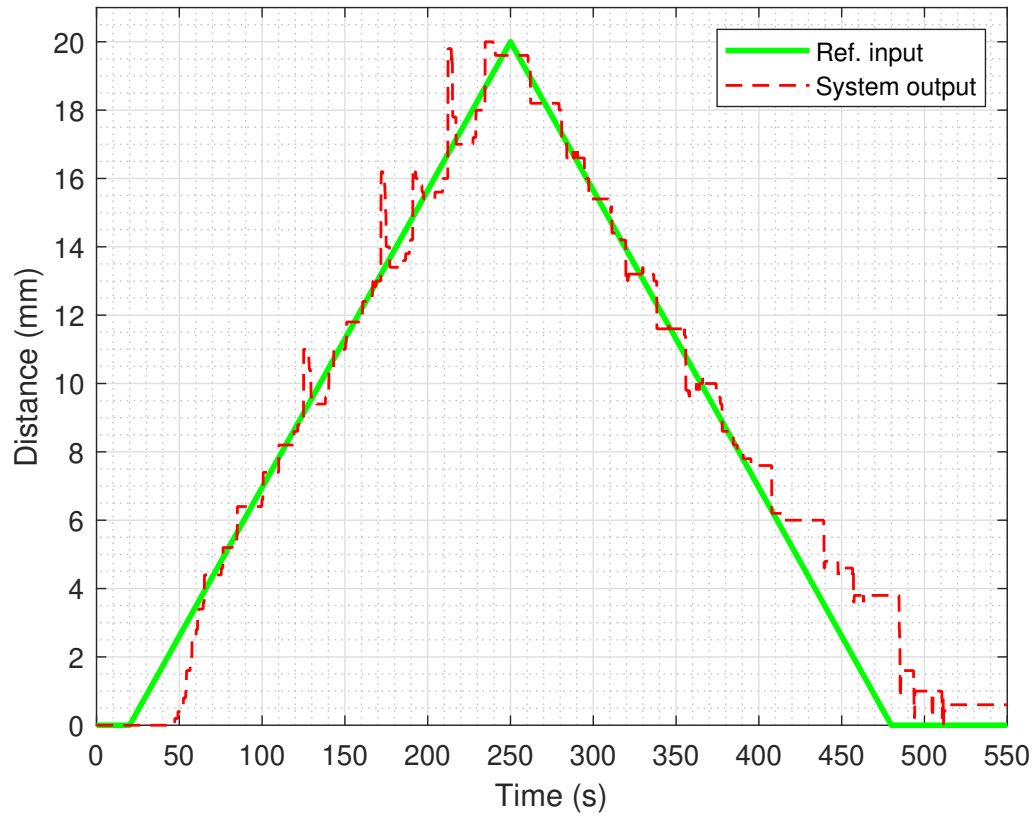


Figure 6.27 Triangular distance reference control

## 6.5. Discussion

In this chapter, the novel actuator spiral has been represented. The processes for its design fabrication control have been discussed. Finally, an application has been suggested. The spiral is a high performance actuator with large actuation strokes of 40 mm in both directions x and y.

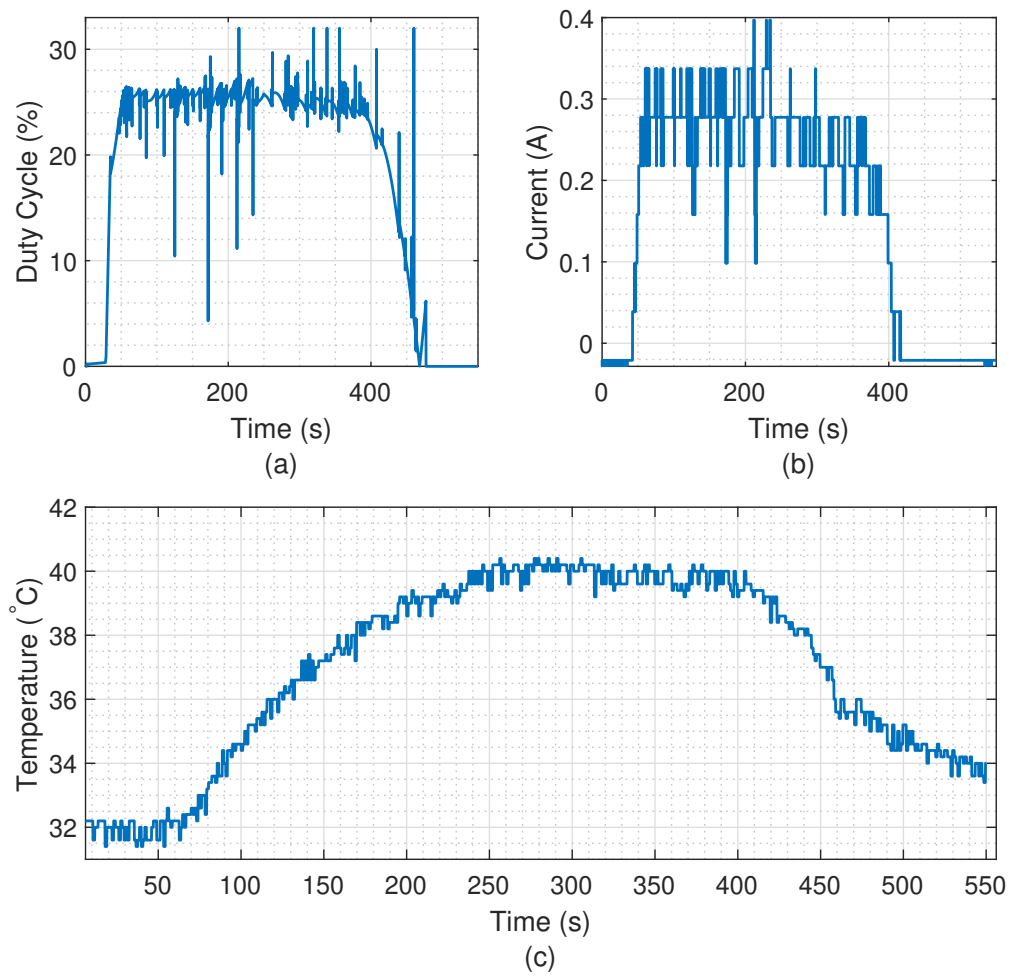


Figure 6.28 For Control in figure 6.27: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

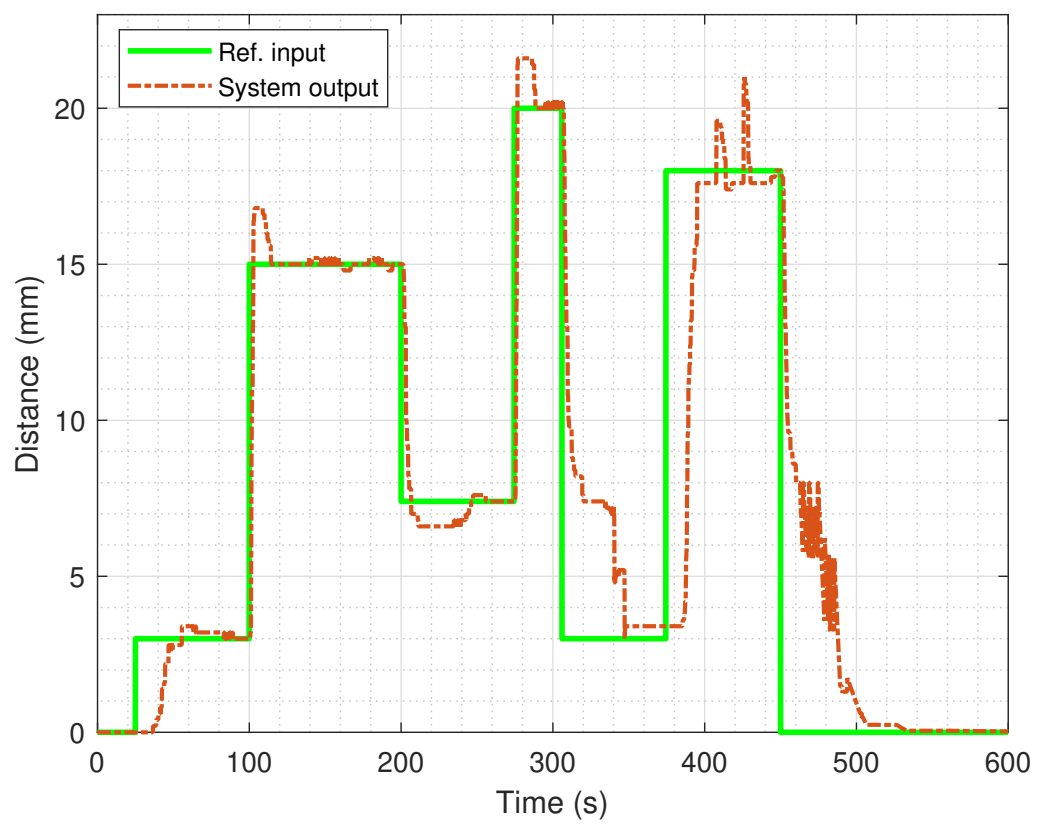


Figure 6.29 Distance reference control

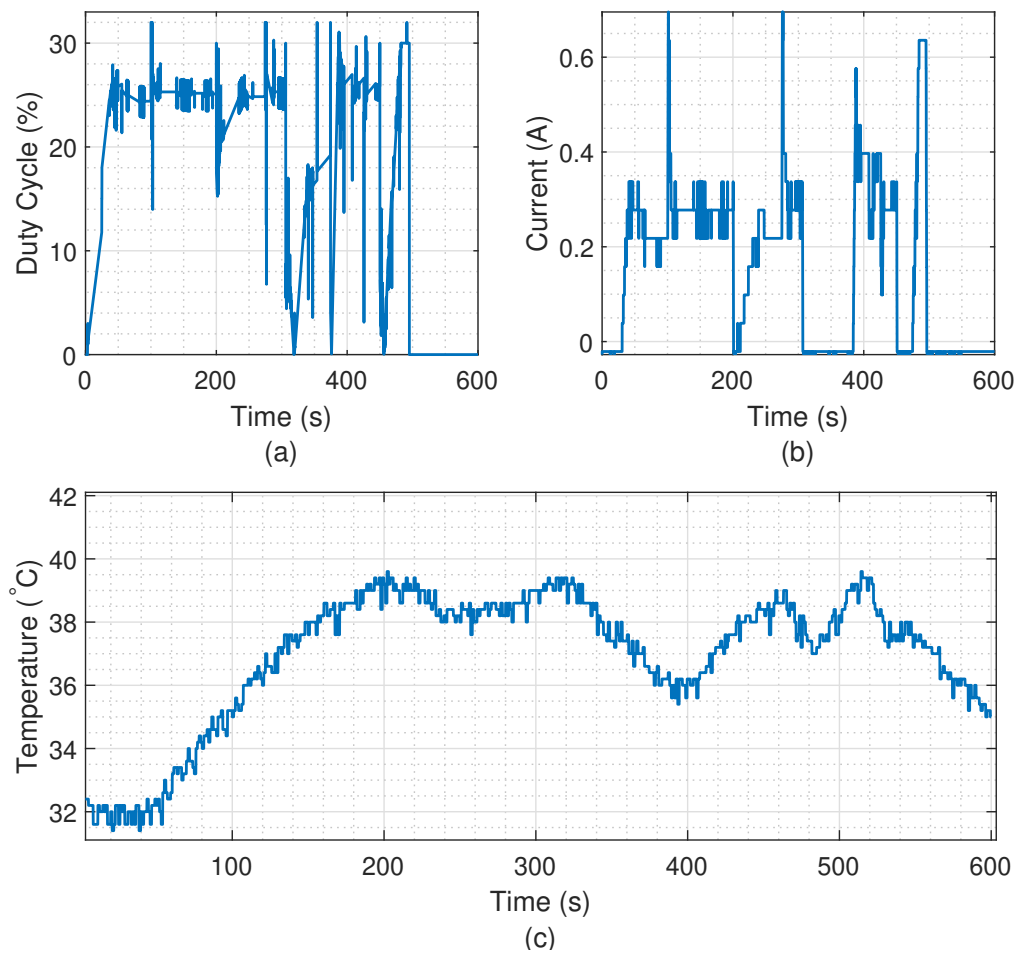


Figure 6.30 For Control in figure 6.29: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

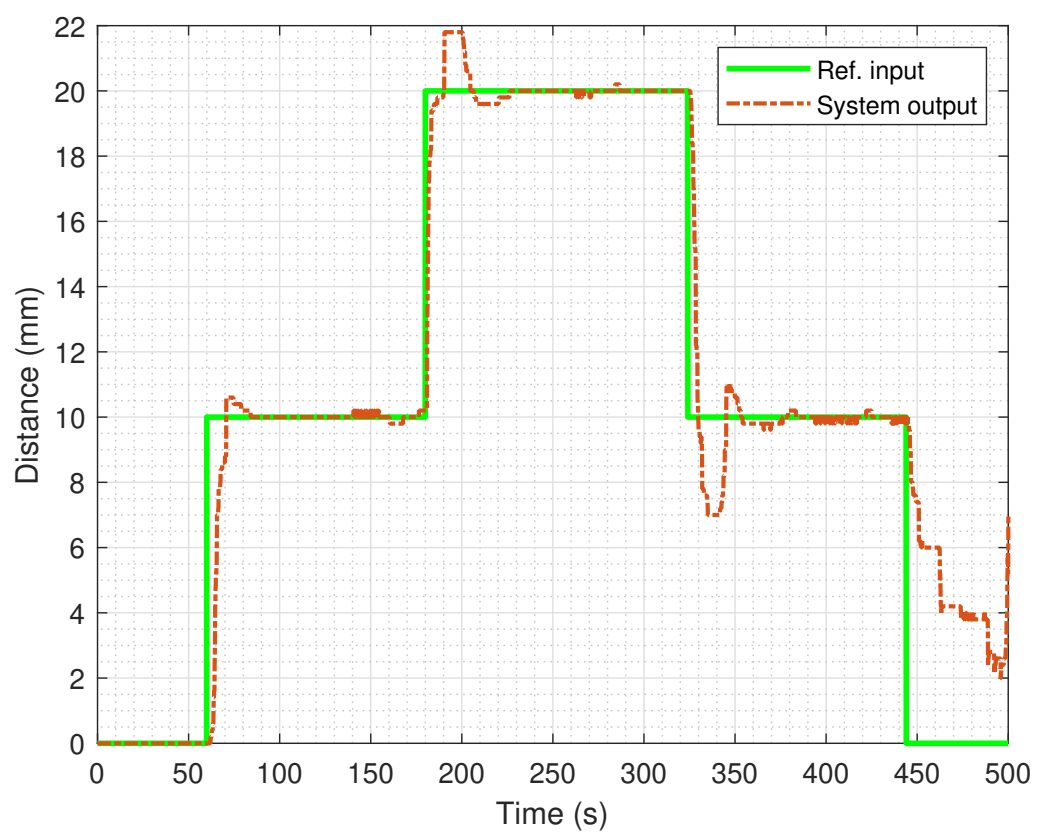


Figure 6.31 Distance reference control

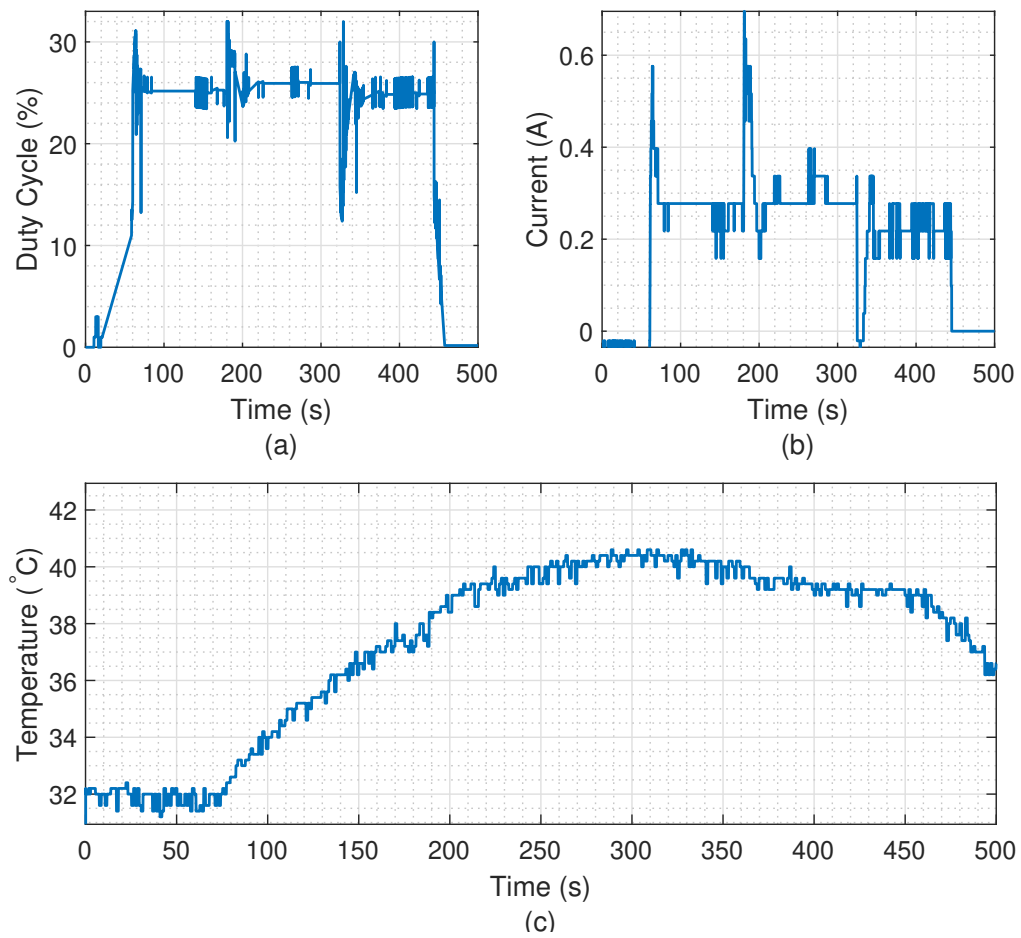


Figure 6.32 For Control in figure 6.31: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

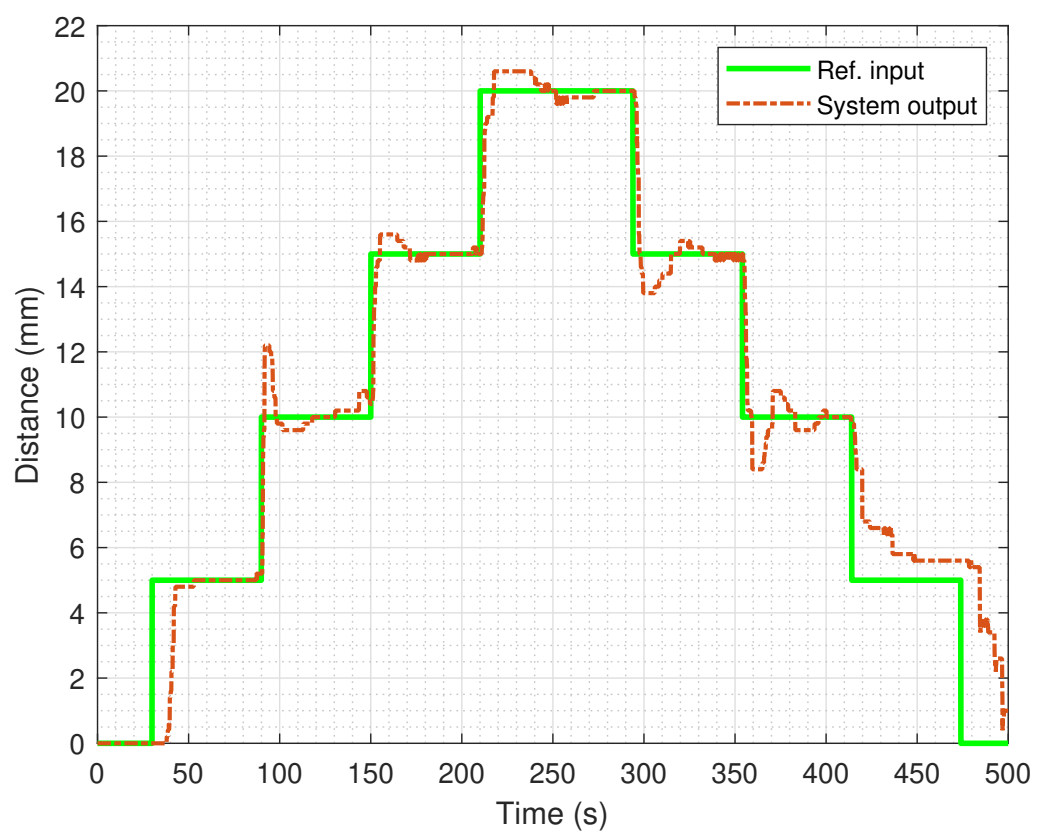


Figure 6.33 Distance reference control

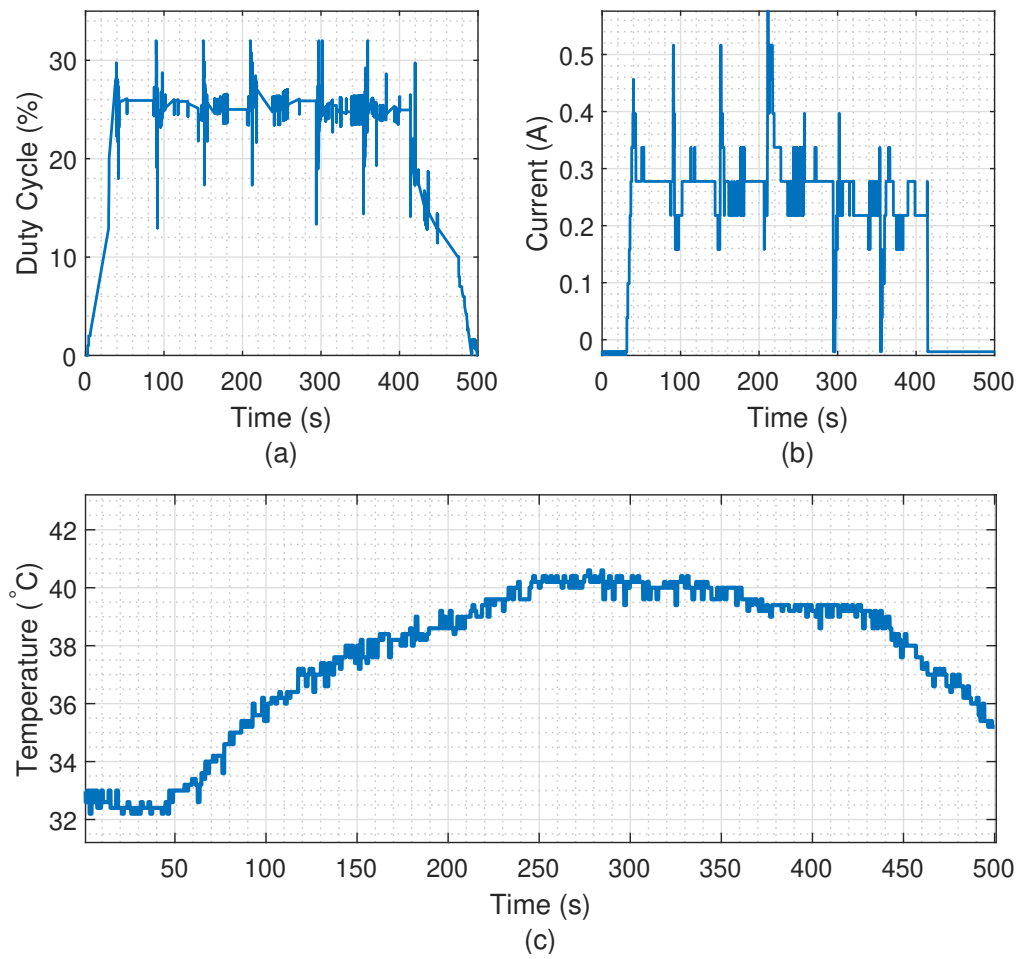


Figure 6.34 For Control in figure 6.33: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

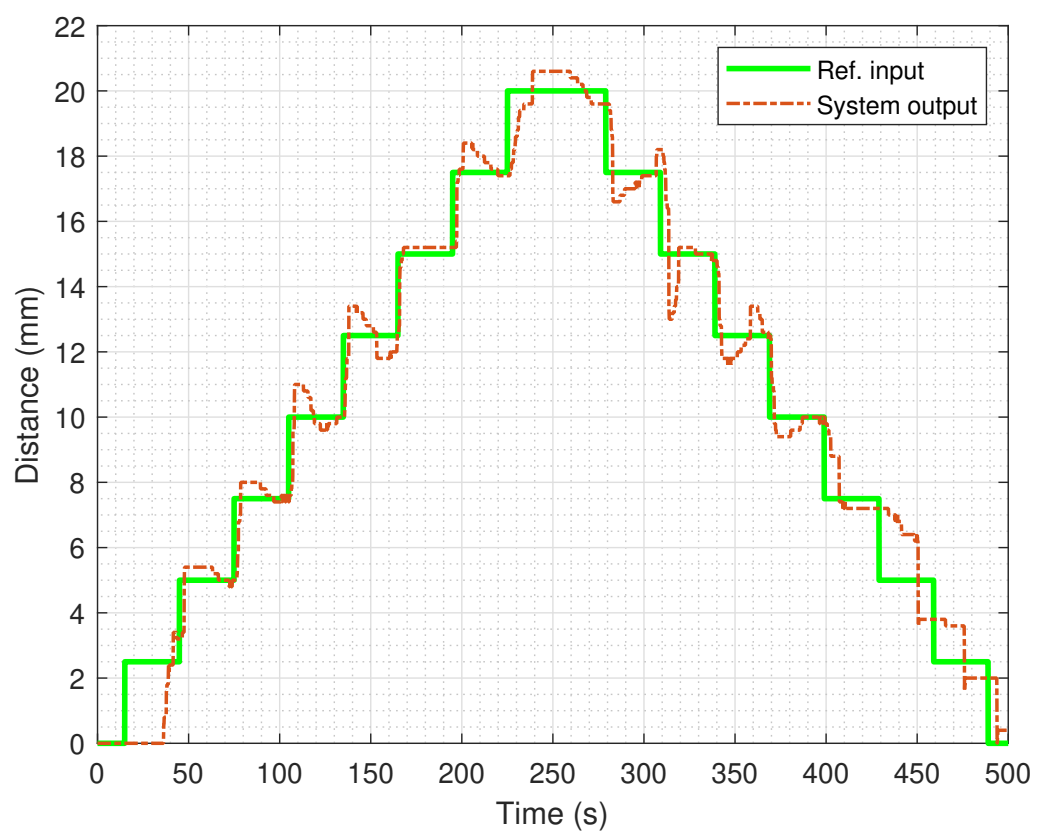


Figure 6.35 Distance reference control

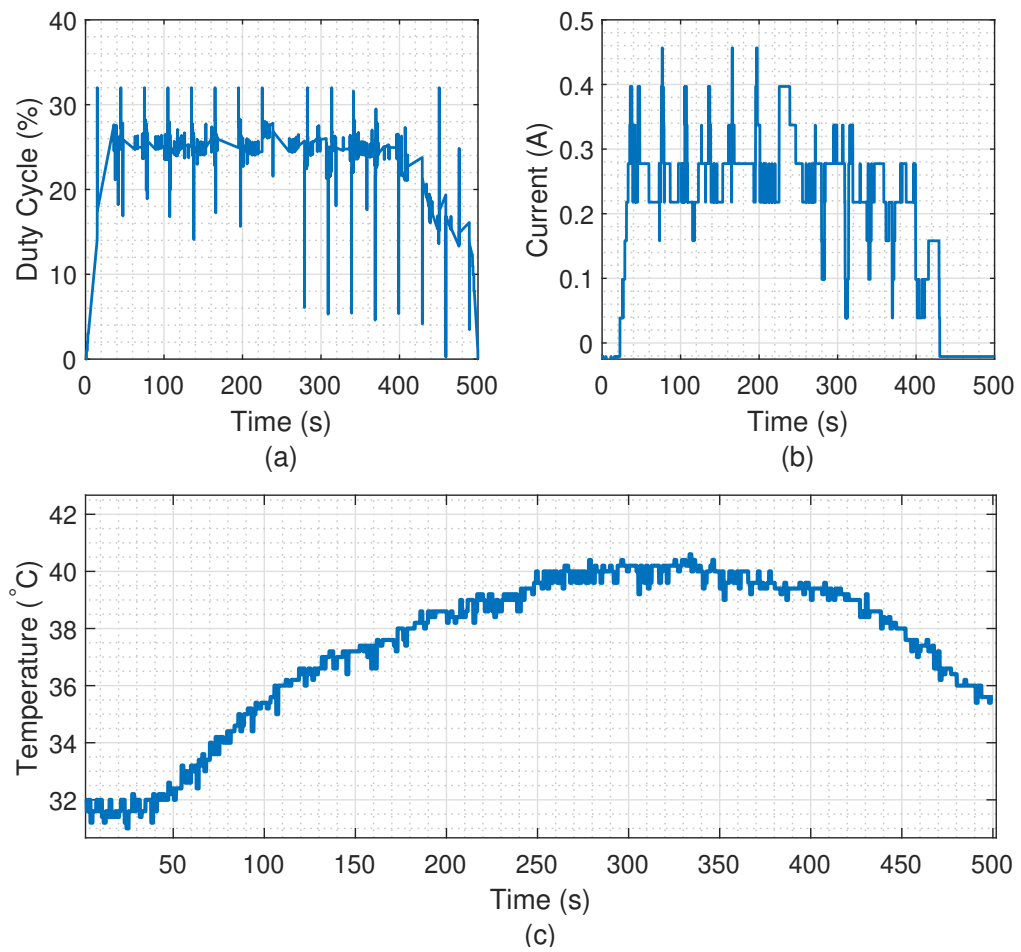


Figure 6.36 For Control in figure 6.35: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

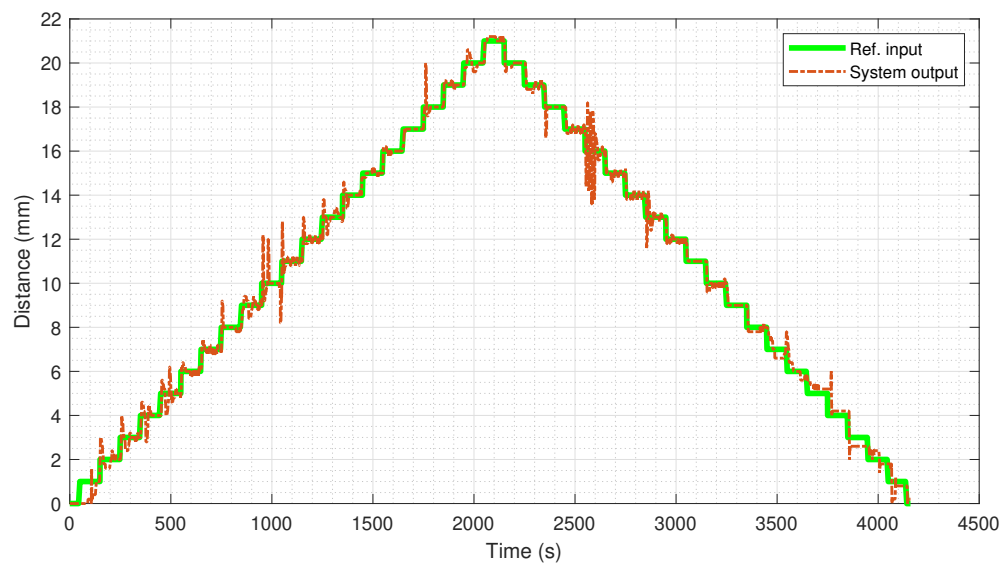


Figure 6.37 Distance reference control

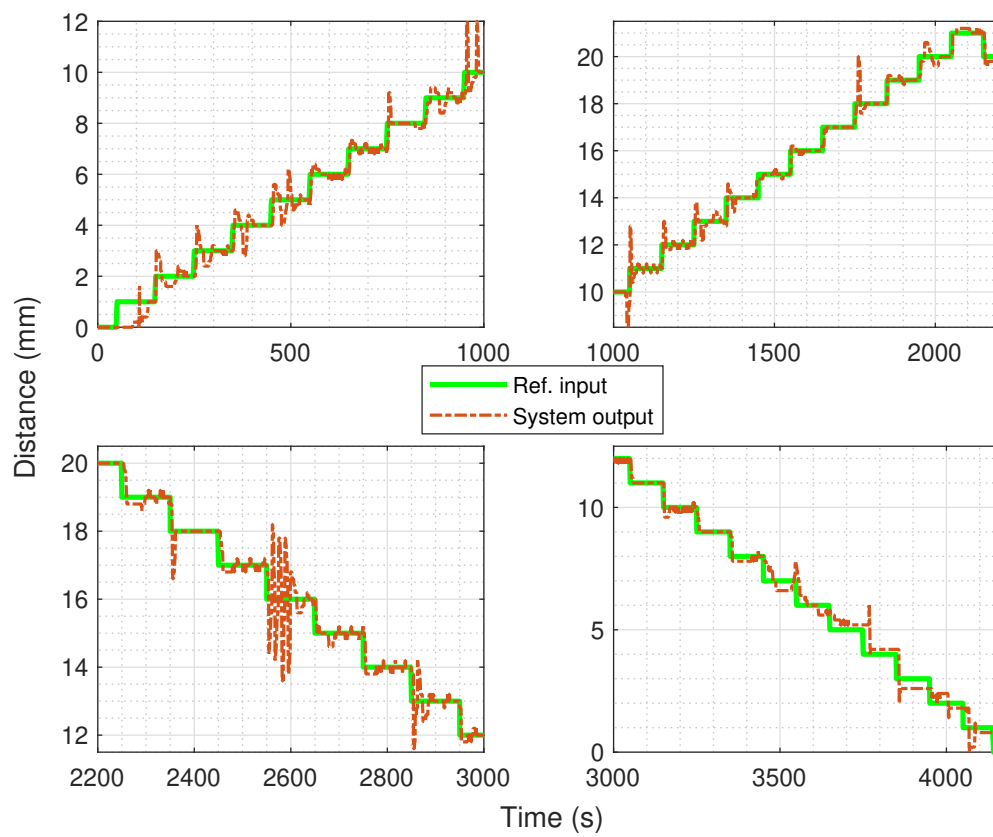


Figure 6.38 Zooming views for figure 6.37

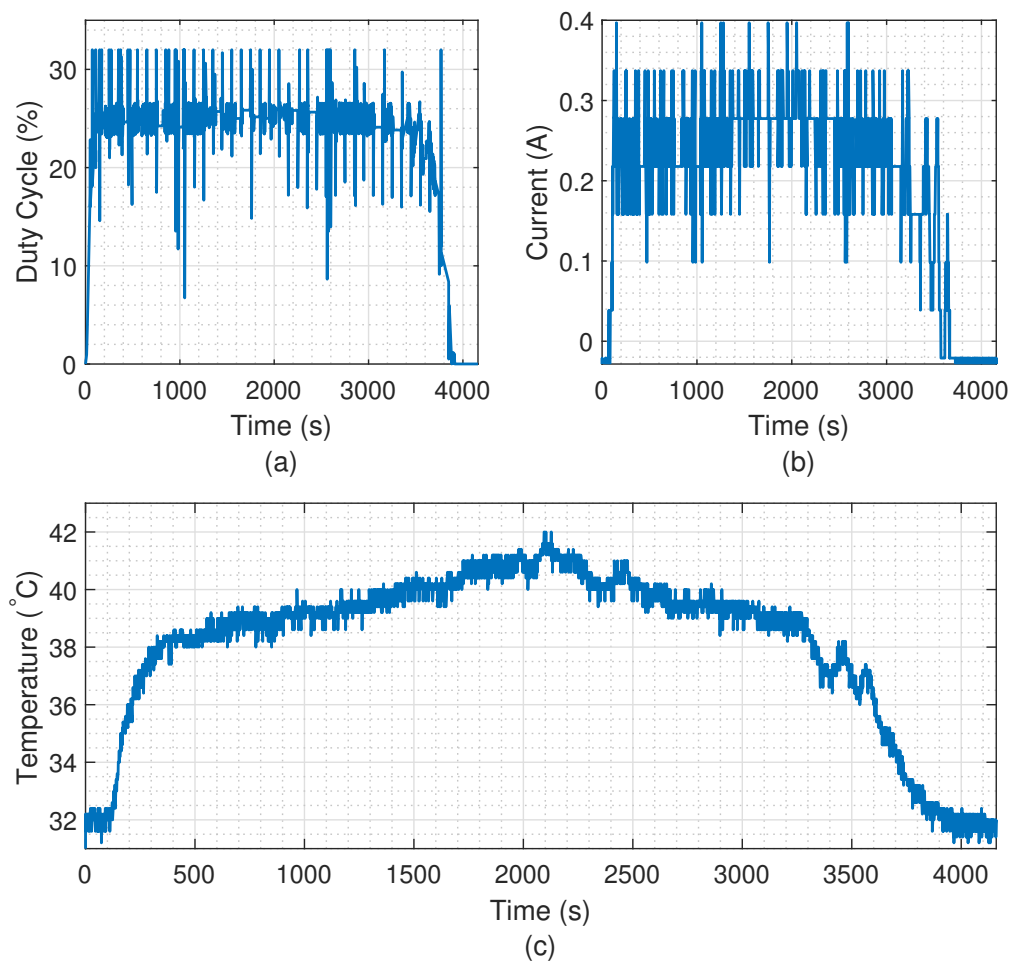


Figure 6.39 For Control in figure 6.37: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

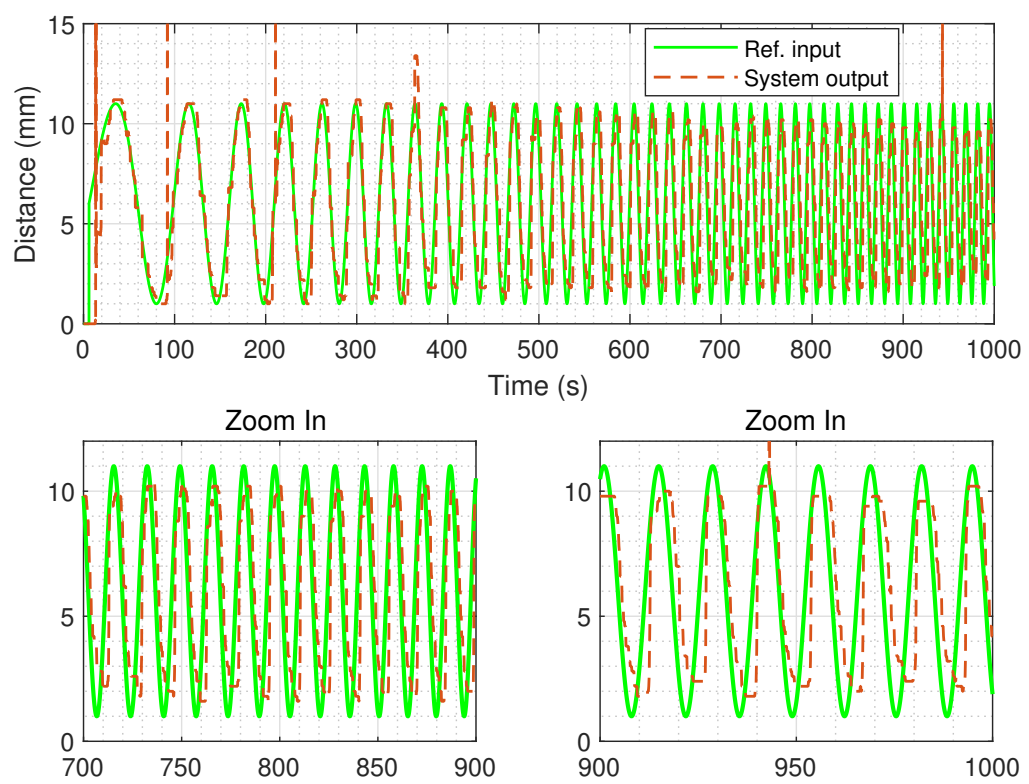


Figure 6.40 Distance reference control

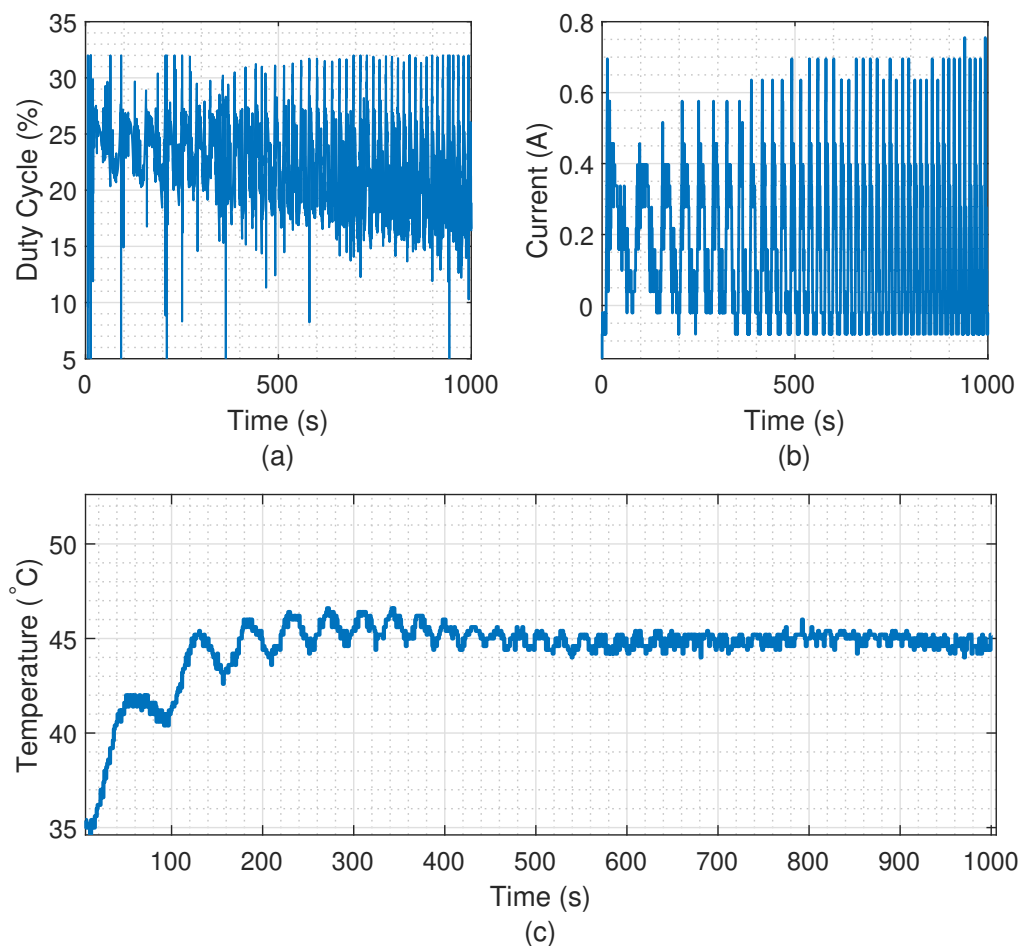


Figure 6.41 For Control in figure 6.40: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

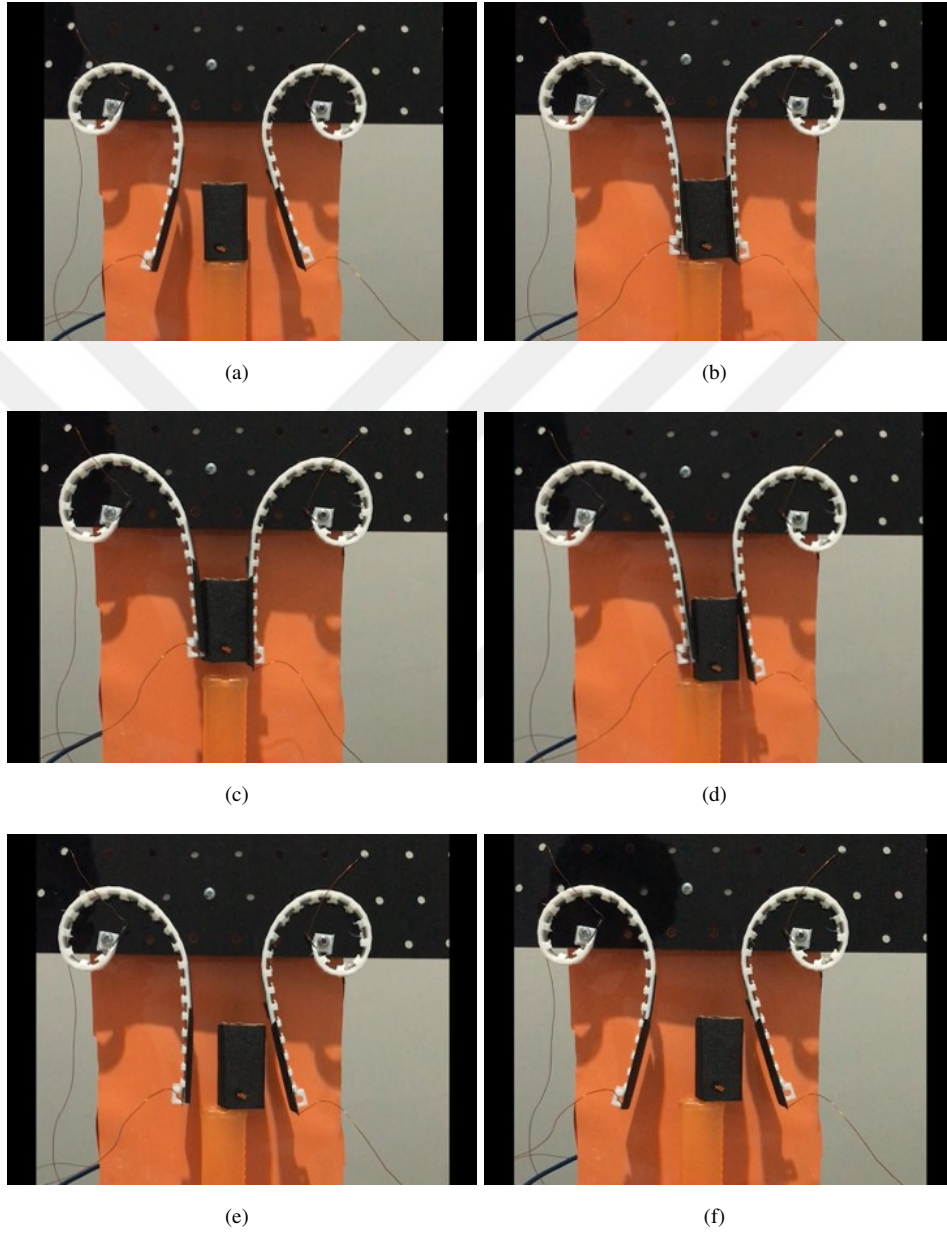


Figure 6.42 Double spiral actuation: (a) Initial position ( $t=0$  s), (b) Holding on ( $t=7.4$  s), (c) Lifting up ( $t=18.6$  s), (d) Lifting down (between 26.4-34 s), (e) Opening ( $t=37.4$  s), (f) Final position ( $t=43.4$  s)

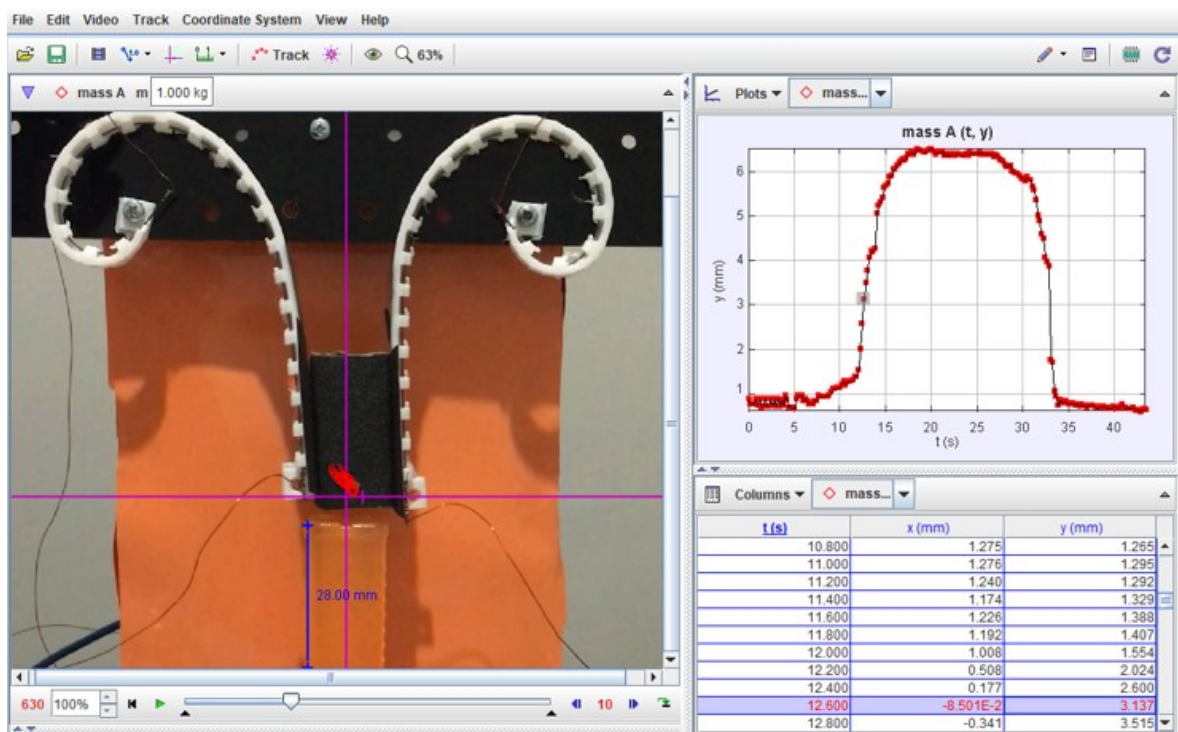


Figure 6.43 For Control in figure 6.40: (a) Control input, (b) Corresponding electrical current and (c) Spiral temperature

## 7. RLS METHOD FOR THE SPIRAL DESIGN

The RLS method used in section 4. is applied here to determine the parameters for the heat transfer model of the composite spiral structure.

### 7.1. Heat Transfer Model For The Spiral

The heat transfer model is the same with the one in equation 31, except the latent heat term. Latent heat term involves the rate of the phase transition obtained from laser displacement sensor directly or from phase transition model. But here, there are some different dynamics due to the composite structure and there is not any model to determine the latent term of the whole composite structure. However, heating with the electrical current passing through the wire and natural convection still works. Thus, in this part of the study, equation 39 is used as the heat transfer model of the composite structure.

$$V\rho C\frac{dT}{dt} = I^2R - hA(T - T_\infty) \quad (39)$$

### 7.2. RLS For The Spiral

The unknown model parameters to be estimated by RLS method are  $CV\rho$  and  $hA$ . In section 4.,  $C$  and  $h$  could be obtained because  $\rho$ ,  $V$  and  $A$  were known. But, calculation of the surface and volume of the structure is attempted due to its pattern with pocket. Considering the SMA wire and TPU material together, referring an equivalent density and also specific heat and heat transfer coefficients are not easy. In spite of all of this, fortunately, RLS method makes a combined estimation like  $CV\rho$  and  $hA$  possible as given in the diagram in figure 7.1 according to equation 40 where  $\delta = T - T_\infty$ .

$$I^2R = \begin{bmatrix} \dot{\delta} & \delta \end{bmatrix} \begin{bmatrix} C\rho V \\ hA \end{bmatrix} \quad (40)$$

As can be remembered from table 3.3, the wire austenite finish temperature is  $58^{\circ}C$ . Hence the electrical current given to the structure is 0.66 A (in figure 7.2) to excite the full phase transition behaviour of the SMA wire.

The temperature is measured on the composite structure in other words, thermocouple has been connected onto the TPU layer as shown in figure 7.3.

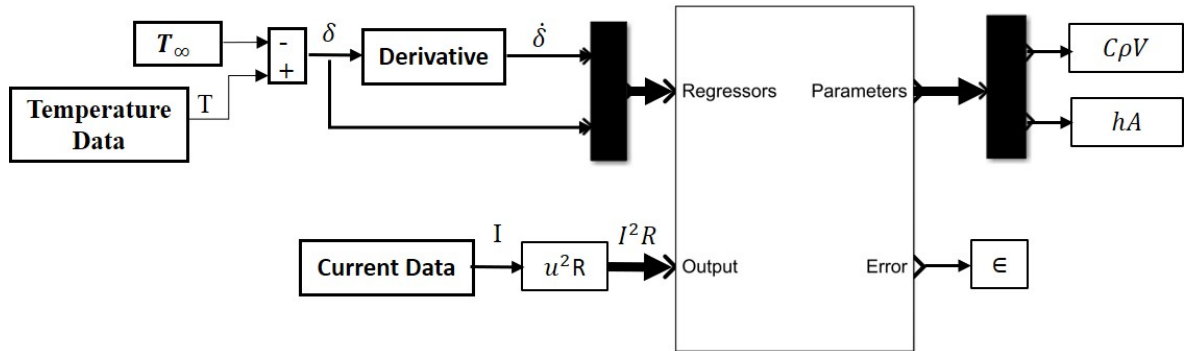


Figure 7.1 RLS estimation diagram for the spiral

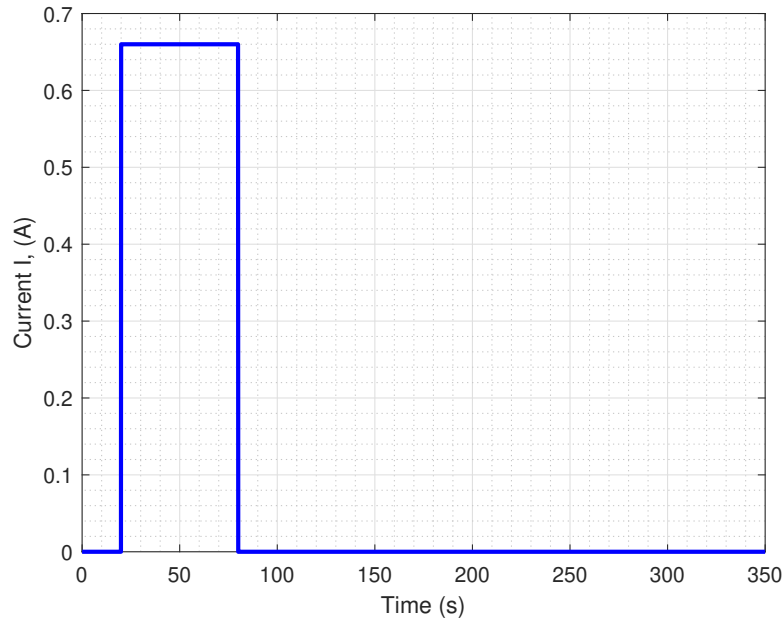


Figure 7.2 Electrical Current for RLS procedure

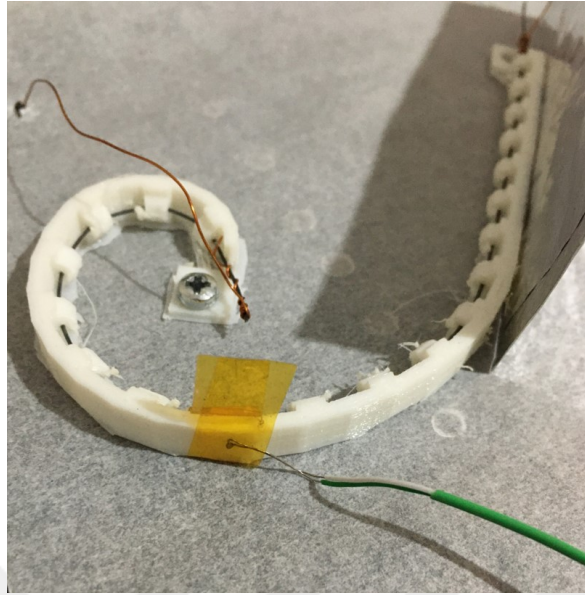


Figure 7.3 Thermocouple connection with a kapton for temperature measurement

### 7.3. Results and Validation

The estimated parameters are given in figure 7.4 and listed in table 7.1 by taking from the convergent parts of the estimation.

After, the estimated parameters are added, the heat transfer model is validated under increasing duty cycles from 25% to 32%. As can be observed from results between figure 7.5 and figure 7.12, the model can follow the measured temperatures for all cases. Maximum  $4^{\circ}\text{C}$  temperature difference is observed in where the electrical current is cut off after maximum temperature. This study is important because it is shown that this simple heat transfer model based on natural convection can be used for this kind of composite structure. Although the combined parameters estimated in this study might be different from separate material properties of each element of the composite, it is clear that the parameters obtained with RLS method are useful for the model.

The model may be improved by adding some other phenomena such as conduction between the SMA wire and TPU body or determining another measurement location on the composite structure in a future study.

Table 7.1 Estimated values of the spiral heat transfer model parameters

|                                  | $C\rho V(J/^{\circ}C)$ | $hA(W/K)$     |
|----------------------------------|------------------------|---------------|
| Estimated Values with RLS Method | 0.18                   | $775.10^{-5}$ |

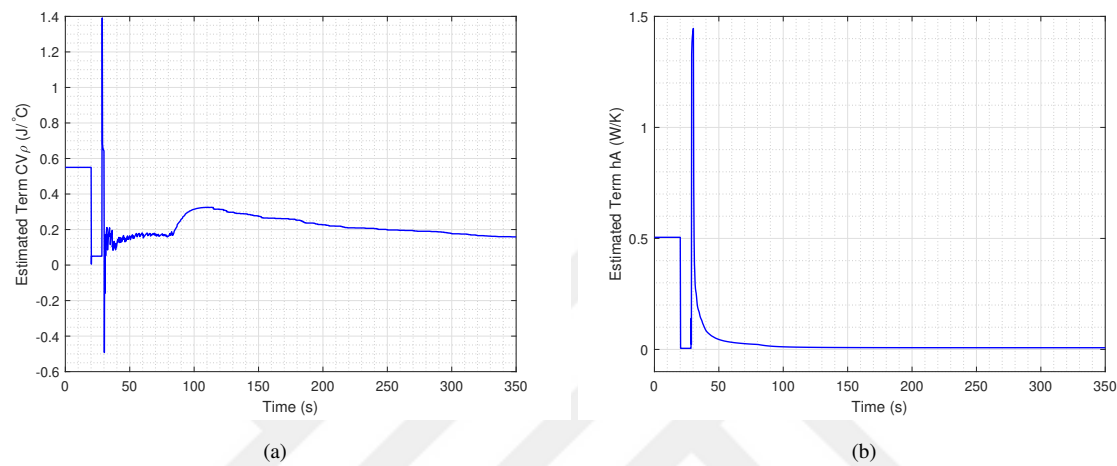


Figure 7.4 Estimations of the terms

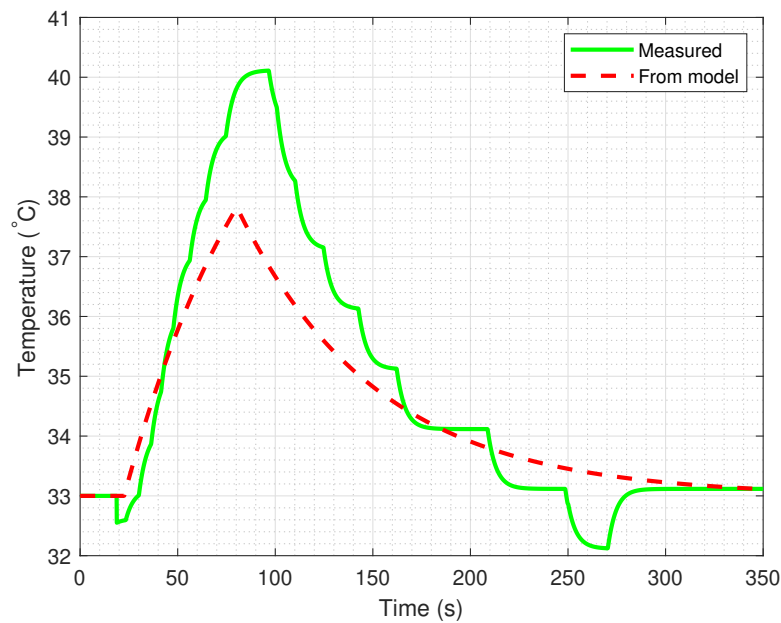


Figure 7.5 Validation of the model including estimated parameters with different temperatures at 25% duty cycle

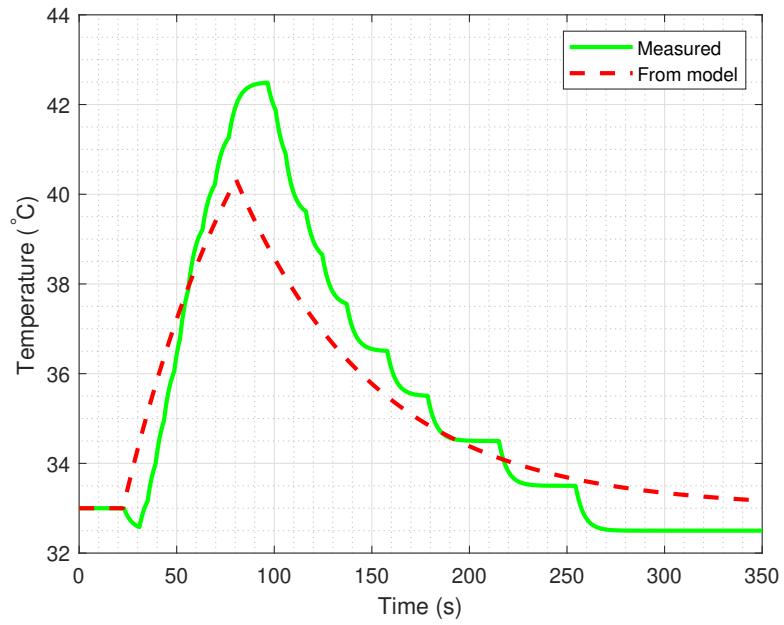


Figure 7.6 Validation of the model including estimated parameters with different temperatures at 26% duty cycle

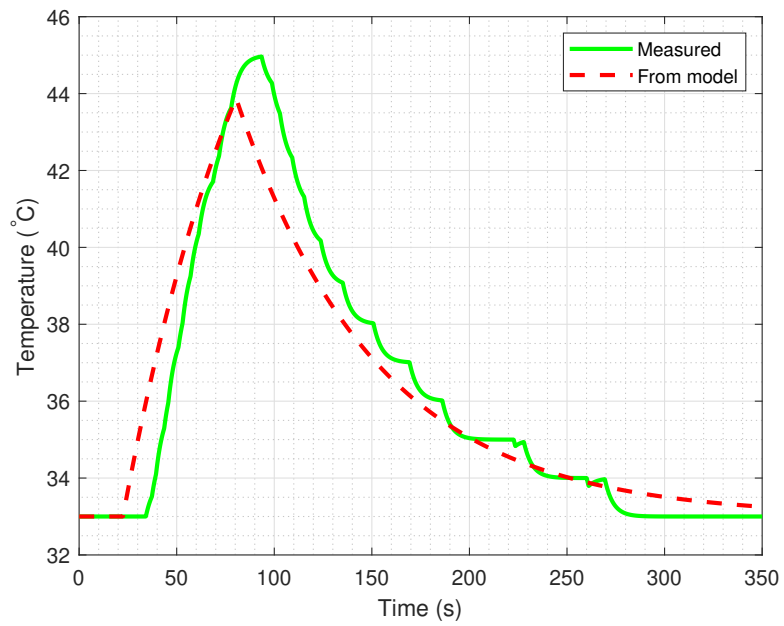


Figure 7.7 Validation of the model including estimated parameters with different temperatures at 27% duty cycle

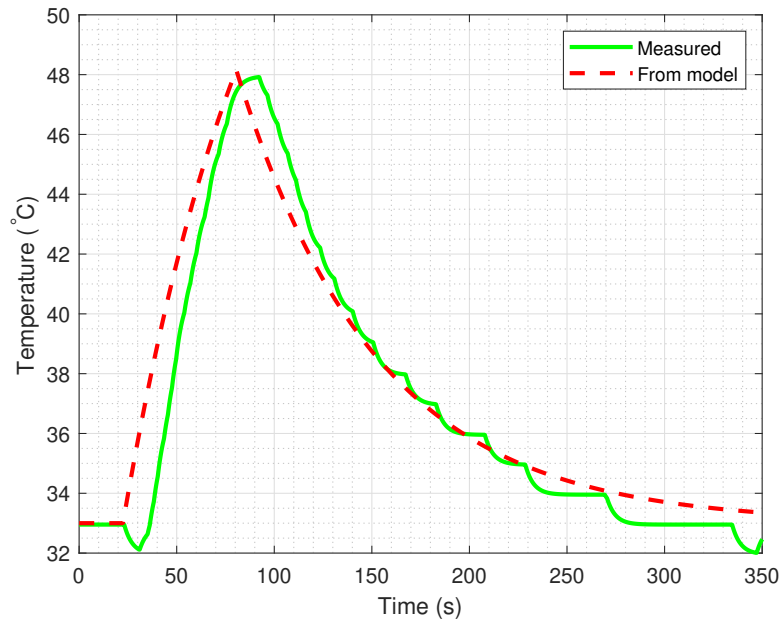


Figure 7.8 Validation of the model including estimated parameters with different temperatures at 28% duty cycle

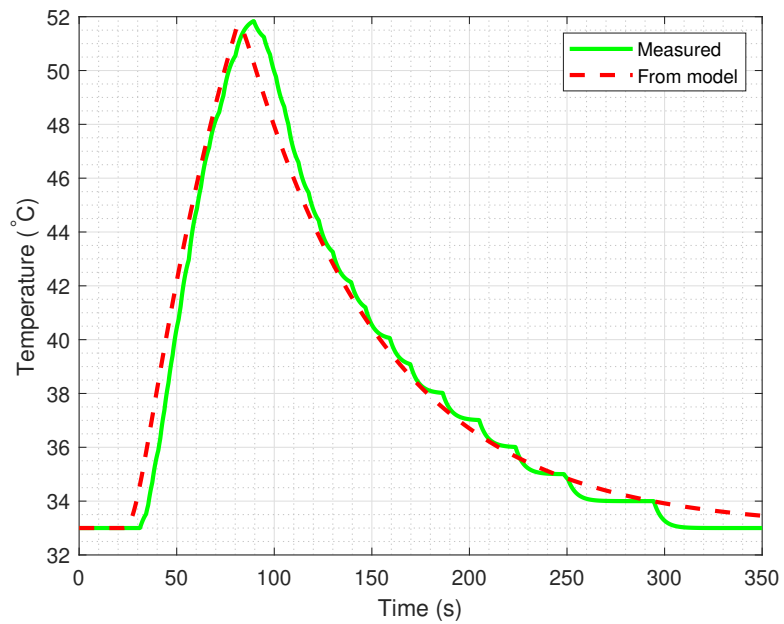


Figure 7.9 Validation of the model including estimated parameters with different temperatures at 29% duty cycle

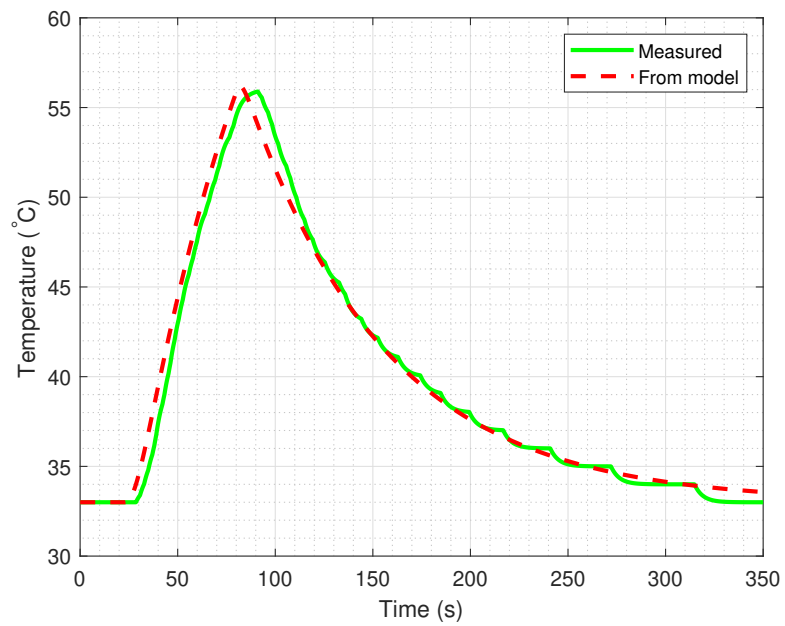


Figure 7.10 Validation of the model including estimated parameters with different temperatures at 30% duty cycle

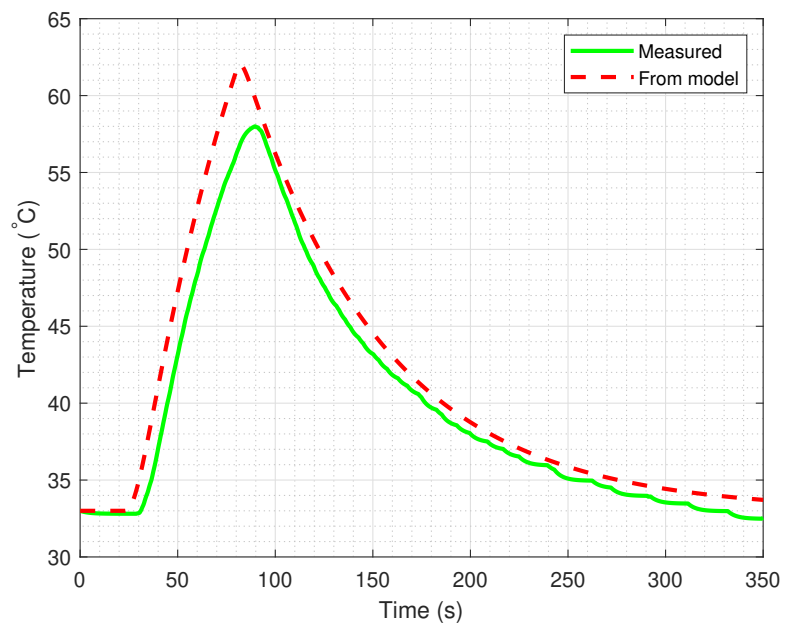


Figure 7.11 Validation of the model including estimated parameters with different temperatures at 31% duty cycle

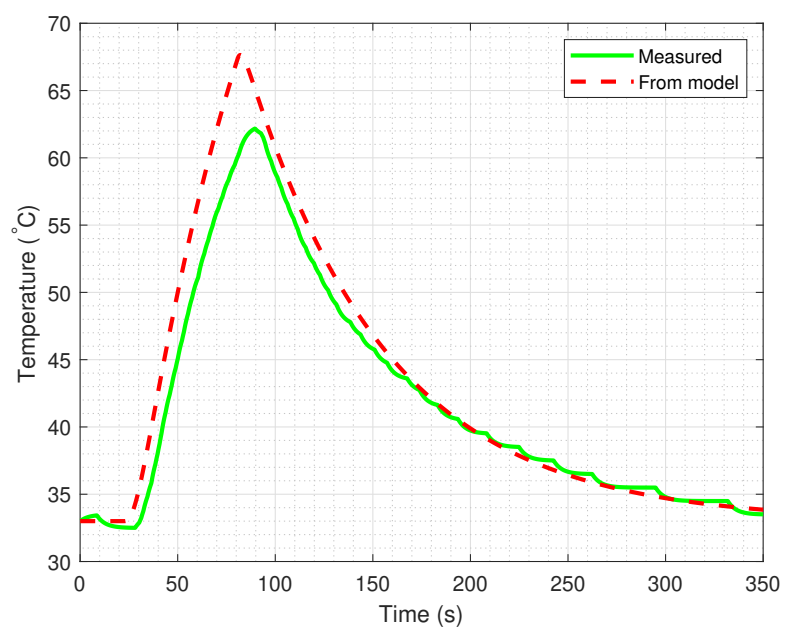


Figure 7.12 Validation of the model including estimated parameters with different temperatures at 32% duty cycle

## 7.4. Discussion

In this chapter, RLS method has been used for the spiral. The suggested heat transfer model including estimated parameters has been suitable for the spiral as well, although the combined parameters estimated in this study cannot be separated.



## 8. CONCLUSION

The SMA wire as an actuator has found many application fields in engineering. For robust and successful designs, the model that represents the wire characteristics closely is important. SMA materials exhibit thermomechanical behavior. Therefore, a heat transfer model is a priority in a full model of the SMA wire.

Generally, heat transfer model is given by considering the rate of change of the temperature with the electrical energy input and the loss of energy with the natural convection. The model has specific heat  $C$  and heat transfer coefficient  $h$  parameters. It is shown that adding latent heat term during the phase transformation into the model provides more accurate model. This term brings along another parameter  $\Delta h$ .  $C$ ,  $\Delta h$  and  $h$  are unknown and to determine them, some methods are suggested in the literature such as empirically methods with recursive tests, or describing the parameters becomes more detailed with identifying some other parameters such as Nusselt number, Reynolds number or Prandtl number.

In this study, RLS method has been performed to obtain the heat transfer model parameters in real time. Two different approaches have been considered for the estimation. The first is the estimation with the phase model and the second one is the estimation with the laser data. For phase model requirements, i.e. to find transformation temperatures and maximum strain under the constant load, SMA characterization procedure has been carried out. Considering its estimation flexibility against the possible changes in the environment which the wire is used and increasing the difference between the model and measured data at  $M_s$  and  $A_f$  temperature points, it has been shown that the estimation with the laser data is better. In common meaning, the parameters estimated by using RLS algorithm have been achieved to overlap onto the measured temperature curve.

Being applicable in a real time application provides considerable priority to the RLS method. It has been shown that heat convection coefficient,  $h$ , which is the most important parameter dominating the heat transfer model, can be estimated with high accuracy for every case.

Improvement by adding latent heat term is important for any control engineering application as well. For instance, desired stroke in a control action can correspond to a temperature value at phase change region. If this region has been modeled accurately, in other words, if the latent heat term has been added, a better control performance is expected.

By doing error analysis, the aim is that better model can be obtained with or without using the estimated parameters. According to this, adding latent heat term into the model and usage of the parameters estimated by RLS method make the model better. Considering changes in ambience, it has been shown that in situ estimation is important.

While collection of data is needed for estimation, fast heating/cooling procedure is applied to frustrate the effect of change at resistance in high temperature values.

Basically, SMA wires or SMA based actuators can be controlled by using strain feedback. PID type controllers have been frequently preferred, many controller design methods have been implemented for robustness.

In this study, strain control of an SMA wire by using PI controller has been discussed. As being widely in the literature, the PI parameters have been empirically tuned by carrying out the experiment and model simulation in Simulink to find the optimal controller gains so as to see the best performance.

Reference signals have been taken as being limited to three specific ranges which are largely martensite, phase transition and largely austenite, respectively to observe control performance. Also, the experiments in the same regions have been repeated for increasing frequencies if the reference input has been the sine signal. Thus, it has been observed that the wire having heating-cooling cycle can be controlled by the same controller gains. Moreover, considering SMA model responses the experimental results, it has been shown once again that RLS method exhibits good performance.

According to norm errors related to the increasing frequencies for sine strain reference inputs, it has been concluded that the controller has difficulty in tracking in this region where phase transition is active and during reference demand with high frequency of 0.2rad/s. According

to the evaluation in terms of the control inputs, i.e. duty cycle % or corresponding currents, it has been observed as expected that the speed of shifts between duty cycles are variably dependent on the reference signals in different phase regions and with different frequencies. Nevertheless, it has been seen in the end that the controller performance with the same tuned gains is good for all cases, though with some delay. Also, it has been shown that the tracking does not go wrong in spite of variable loading. The controller is robust against this effect.

Soft composites have a prominent place in the actuator design area. The actuator can be produced easily, in a fast and cost effective way. Two-way actuators can be designed by using variable materials.

In this study, fabrication, selection, constraints, control of the spiral as a novel soft SMA-based composited design have been discussed. Soft body of the design is produced from TPU material. Two-way actuation has been achieved by both TPU soft body and novel geometry of the actuator body, i.e. the spiral shape. A very simple and cost effective fabrication method by using 3D printing method (embedding wire with the pausing-resuming property of the 3D printer) instead of using other methods such as molding or curing has been presented.

After fabrication of four types of spirals having different number of pockets opening to the ambient, the optimal one is selected. In this period, cooling performances of the spirals, in other words, speeds of a full actuation cycles with heating/cooling and actuation strokes are investigated. On the one hand, it is observed that fully closed design has poor actuation stroke, on the other hand the arches on the spiral which connect the SMA wire to the soft body start to be thinner if large pockets are preferred for fast cooling. Image processing method following video recording of the spiral motion is used to carry out all these analyses.

It has been shown that large actuation strokes of 40 mm in both directions x and y can be reached by means of the spiral design, although there can be a relative motion between TPU structure and SMA wire due to the tolerance in wire integration method during production of the structure. Additionally, the structure can return to the pre-actuation state again.

Electrical current constraint is determined for the optimal spiral to prevent the wire sticking out. Then, the spiral is controlled by PID controller as long as the electrical current is kept in this constraint. Good tracking performances have been observed for different strain references.

Finally, an application is presented by using two of the spirals. A weight of 6.5 gr can be lifted up and then, it can be put the initial position by a narrow margin. Especially, it is very important and remarkable that this action lifting up of 6.5 mm is completely made as automatic. The spiral actuator design can be utilized to the equivalent designs in [46, 63, 64, 76, 77] as a good alternative.

Last but not least, the RLS method has been applied for the spiral design as well. It has been shown by presenting the results and validation of the RLS method that this simple heat transfer model based on natural convection can be used for this kind of composite structure in this study. Although the combined parameters estimated in this study might be different from separate material properties of each element of the composite, it is clear that the parameters obtained with RLS method are useful for the model.

## 9. FUTURE WORK

The next steps about the studies in this thesis can be composed as follows:

- RLS method can be tested for other components of the thermomechanical model of the SMA with some linearization methods.
- Integration of the wire into a application and a study to observe how RLS performance is in a real time estimation could be suggested as future work. RLS estimation algorithm could be run for another model detailed by considering changing resistance as a function of temperature.
- An accurate model of the material is important for superelastic SMA-based vibration control as considered in [122]. The identified heat transfer model parameters in our study is also applicable for the mechanical response modeling of superelastic SMAs.
- New controller gains with better performance can be obtained by working on a model-based controller design.
- The spiral design is open for improvement in terms of actuation stroke and time.
- Considering aspect ratio between TPU and the wire or using other wires having different diameter, one can design any kind of composite structure according to desired stroke specifications.
- Some cooling methods can be used to reduce the actuation time.
- The spiral can be implemented to the many variable applications such as gripper or soft robots.
- Controlability of the spiral has been shown.
  - Position control can be made for lifted weight in the application in this study.
  - Some other control methods may be tested on the spiral.

- The model for the spiral can be improved by adding some other phenomena such as conduction between the SMA wire and TPU body or determining another measurement location on the composite structure in a future work.



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