Chapter 5

Development of Faster SMA Actuators

Atta Muhammad Nizamani, Jawaid Daudpoto and
Muhammad Ali Nizamani

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.69868

Abstract

Large cycle time, resulted from slow cooling, is the core hindrance to the wide spread applications of shape memory alloys (SMAs) as actuators. This chapter discusses a novel cooling technique to decrease the cycle time of SMAs. Under this technique, the SMA actuator of 0.15 mm diameter was run through a grease-filled Polytetrafluoroethylene (PTFE) tube of 0.5 mm outside diameter. Later, same tests were repeated with oil filled PTFE tube. The test results conducted in ambient air were used as standard for comparison. The actuation current in ambient air was set at 210, 310 and 410 mA. While testing with heat sink, i.e. grease and oil, the SMA was heated with 210, 310, 410, 500, 615 and 720 mA currents for 1 and 2 seconds, whereas the SMA was heated for 1 second only with 810 mA current. It was found that the grease cooling reduced the cooling time up to 30% and oil cooling by 20%, as compared to the ambient air-cooling time. However, the grease-cooled actuators had shown less strain, and their response was non-linear at many instances. Heat loss to the sinks resulted to more power consumption than that in ambient air cooling for equivalent amount of strain.

Keywords: SMA actuators, long cycle time, SMA cooling, Teflon tubing

1. Introduction

The need for miniaturization and lighter systems has resulted in the development of smart actuators, which are compact in size and lighter in weight. The shape memory alloys (SMAs), also called the smart alloys, were discovered by Arne Ölander in 1932 [1]. Various properties of SMAs, like high work output as compared to other conventional actuators, silent, clean and spark-free operation, design simplicity and easy miniaturization, have attracted researchers and engineers to use them as actuators in several applications [2].

The operation of SMA actuators is considered to be simple. SMA actuators in many applications are in the form of a thin wire and their diameters ranging from 0.025 to 0.51 mm [3]. The motion created in SMAs is due to a molecular rearrangement in their crystalline structure when phase transformation takes place, as shown in **Figure 1**.

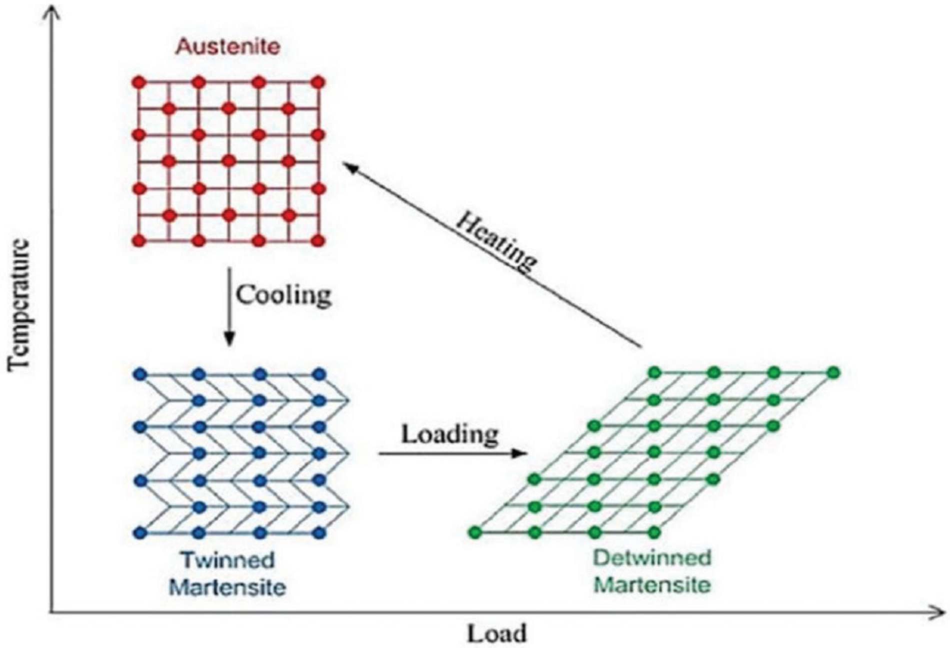

Figure 1. Phase transformation in SMAs [4].

The phase transformation takes place at certain temperatures called phase transformation temperature. The phase transformation temperature is determined by the composition and heat treatment methods applied to the SMAs. Low temperature phase is known as martensite, whereas, heating results in transformation to austenite phase. SMAs are relatively soft in Martensite phase and possess smaller value of Young's modulus, whereas they are hard in Austenite phase with higher value of Young's modulus.

2. SMA design challenges

The design challenges in SMA-based systems are to succeed over the limitations incorporated with SMAs. Some of the SMA limitations are relatively small usable strain, low operational frequency, low controllability, low accuracy and low-energy efficiency. However, low operational frequency resulted from large cycle time is widely reported in literature as core hindrance to wide spread applications of the SMAs [5–7]. The operational frequency of SMAs is given by Eq. (1) (working frequency of SMAs).

$$f_w = \frac{1}{t_h + t_c} \tag{1}$$

http://dx.doi.org/10.5772/intechopen.69868

Where

f_w = Working frequency of SMAs

t_h = Heating time required by SMAs

t_c = Cooling time required by SMAs

The cycle time in SMAs is defined as the total time required by the SMAs to contract and expand, hence completing its full cycle. Cycle time is the algebraic sum of heating time (i.e. contraction time) and cooling time (i.e. expansion time). The heating time of the SMAs can be easily reduced by increasing the magnitude of actuation current, whereas the cooling rate is redistricted by the rate of heat transfer rate to the environment surrounding the SMA specimen. The actuator response time also depends upon the size and shape of the actuators. The SMA actuators with smaller diameter cool faster as compared to those having larger diameters. However, this will affect the loading capacity of SMA actuators. **Figure 2** is developed by using the technical data provided by Dynalloy, Inc., the SMA manufacturer [3]. It shows the relationship between the loading capacity of SMA actuators and cooling time required by SMA actuators of various diameters in ambient air at room temperature. However, the time required to restore final 0.5% strain is not considered.

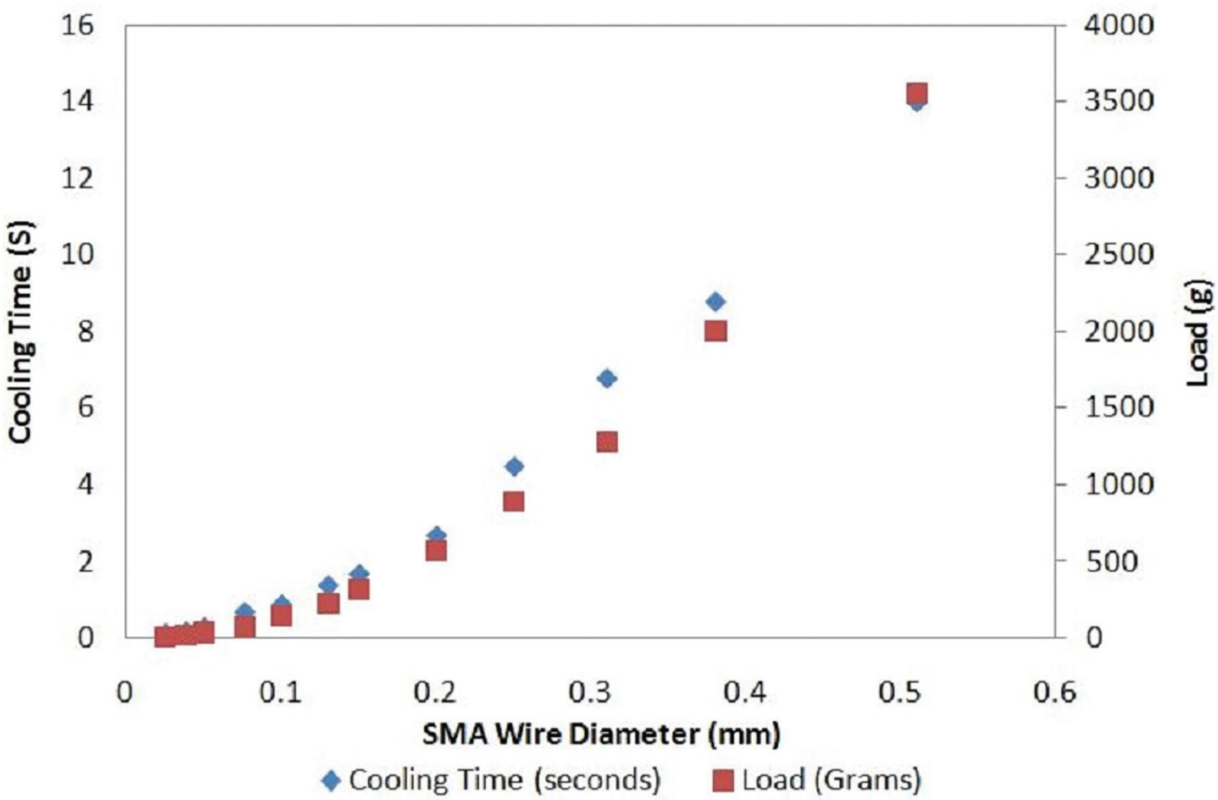

Figure 2. Relationship between wire diameter, cooling time and safe load for SMA wire actuators.

From **Figure 2**, it can be observed that the cooling time required by the smaller diameter SMAs is relatively small. However, the smaller diameter SMAs can carry little load as compared to those carried by SMAs having larger diameter. Therefore, the need is to develop the faster cooling mechanisms for SMAs.

Large cycle time is core hindrance to the SMA applications in several areas, including automobiles, robotics, biomedical, etc.

3. Practical applications of faster SMA actuators

Around 200 actuation tasks are performed in a family car [8]. The actuators required to operate several functions in a car are categorized as (a) low-power actuators for comfort and aesthetic aspects, (b) actuators having high power to operate various control mechanisms of vehicles and (c) the actuators with high frequency to control engine performance [9]. The SMA actuators are being used in first category of actuators, as applied by Mercedes, BMW, General Motors (GM), Hyundai, Ford, Porsche and Volkswagen (VW) to actuate lumbar support in the car seats for passenger comfort [10]. The SMAs are applicable in second category of actuators; however, these are still to be studied for this category, whereas due to low working frequency, resulting from large cooling time, the SMA actuators are either not suitable or less suitable to be applied against third category of actuators.

The SMAs due to their ability to produce linear motion, high power to weight ratio, light weight and compact size are widely being used in several areas of robotics. Some common SMA applications in robotics are robotic grippers [11], human organ orthotics like a foot ankle orthotics [12], rehabilitation robots like a wearable elbow exoskeleton [13] and bio-inspired fish-like robots like i-tuna and dragon fly robots [14, 15]. However, large cooling time is reported to be the core limitation of SMAs in the field of robotics [8, 12, 16, 17].

The biocompatibility of SMAs has made them feasible to be applied in several applications related to biomedical sciences. SMAs are being used in neurology, cardiology and interventional radiology in different ways [18]. SMA-actuated surgical needles and catheters, artificial heart, artificial head and drug-delivery valves are some of the most prominent SMA applications in area of biomedical [19–22]. However, low working frequency resulted from large cooling time is reported to be the serious issue [19, 22, 23].

The SMAs due to attractive morphing properties and ability to withstand dynamic loads are used in several aerospace applications. Some of the noticeable aerospace applications of SMAs are in wing morphing, for example, the DARPA project for development of smart wings [24], SAMPSON project to enhance SMA applications in aircraft engine nozzles at inlets to obtain flying benefits according to flight conditions [25] and reconfigurable engine nozzle fan chevron by Boeing [26]. SMAs are equally applicable in various space research applications, for example, folding and unfolding mechanisms for solar panels on Hubble telescope [27], actuation of valves and apertures on board of Rosetta mission (2004) and Pathfinder–Sojourner Mission (1997) [28]. Their applications can still be enhanced to various actuation applications in spacecrafts, either manned or unmanned [29]. However, the limited working frequency of SMAs resulting from large cooling time is core issue in many aerospace engineering applications [30, 31].

4. Literature review

Several studies have been conducted to reduce the cooling time required by SMAs to regain martensite phase; however, no any unique method has been proposed. In the following passages, a review of such studies is presented.

Loh et al. [32] used silicone grease as heat sink. The authors filled the grease in a metal tube of outside diameter 0.8 mm and inserted 600 mm long and 0.3 mm diameter SMA actuator in the tube.

In reported method, the heat dissipation from SMA to sink was achieved at 5°C per second. The SMA actuator was heated by electrical current supply of 2 A, with a duty ratio of 0.4. The martensitic phase transformation also depends upon the mechanical load connected to the wire; however, in the reported work, the SMA actuators are made to lift up 3 kg mass. The system had following listed limitations:

i. The metal tube is solid; therefore, it is likely to affect the system's flexibility.

ii. Since the actuator was jacketed around with coolant, the heat loss at 1.75°C per second was observed during the actuation. Heat loss during the actuation will increase the heating time required for phase transformation.

In another study, Loh et al. [33], while developing the SMA-actuated prosthetic hand, used stainless steel (SS) tubes to enhance the heat transfer rate from SMAs to the environment. The authors ran 2 SMA wires, each 500 mm long and 0.3 mm diameter, through the SS tubes. The SMA actuators were actuated with 50–70 V via pulse width module (PWM). In the reported method, the actuation voltage ranging from 50 to 70 V is unsafe for many applications and uneconomic as well.

Taylor and Au [17] developed an SMA-actuated prosthetic hand. The authors applied the forced air-cooling technique for rapid heat transfer from the SMA wire actuators to the surrounding environment using a small fan. The forced air cooling with a fan produced satisfactory results; however, this method is not applicable in the miniature applications where space is a major constraint.

Cheng and Desai [34] applied water circulation through the SMA actuator arrangement for cooling purpose. The SMA spring actuator was enclosed inside a silicone tube of inside diameter 1.98 mm. The reported method resulted in 0.33 Hz frequency. However, in the presented research, the working frequency of 0.33 Hz was achieved in ambient air cooling when the SMA actuator was heated with 410 mA actuation current. The water circulation, as applied in reported research, is likely to increase the system's complexity as a pump will be required to circulate the water through the actuator, also special sealing arrangements are necessary to avoid water leakage out of actuator. Therefore, the reported system will be bulky and not feasible in miniature applications.

Pathak et al. [35], in order to examine the performance of various cooling media, conducted a comparative study. The authors conducted tests on various SMA actuator samples whose diameters were ranging from 0.1524 to 0.508 mm and each SMA actuator sample was 177.8 mm long. The authors tested the SMA actuator samples in still air, forced air convection, mineral oil, thermal grease and water as cooling media. In still air, the authors found that SMA wire diameter had major impact on the cooling time. It was observed that the values for coefficient of heat transfer (h) for 0.1524 mm diameter SMA wire was 153 W m^{-2} K^{-1}, whereas value of h for 0.508 mm diameter SMA wire was 68 W m^{-2} K^{-1}, which is 44% smaller than that of 0.1524 mm diameter SMA wire. In forced convection in air, the authors set the air flow rate at 625 ft min^{-1} using a fan. It was noticed that the value of h for 0.1524 mm diameter SMA wire was nearly 650 W m^{-2} K^{-1}, whereas that of 0.508 mm diameter SMA wire was nearly 400 W m^{-2} K^{-1} which is 40% smaller than h values for 0.1524 mm diameter SMA wire. Since the air was enforced using a small fan which is not feasible for miniature applications, for example, in minimal invasive surgery, a separate controller will be required to vary the fan speed in order to adjust the speed of airflow in the SMA actuator, at the same time, this will lead to more power consumption to operate a fan and a possible controller. Later, the authors tested the SMA actuators jacketed around with mineral oil. The value of h for 0.1524 mm diameter SMA wire was found to be 1000 W m^{-2} K^{-1}, whereas the h value for 0.508 mm diameter SMA wire was nearly 510 W m^{-2} K^{-1}. This shows a reduction of 49% in the h values for 0.508 mm diameter SMA wire as compared to that of 0.1524 mm diameter SMA wire. As compared to forced air convection, the h value for 0.1524 mm diameter SMA wire was improved by 350 W m^{-2} K^{-1}, whereas the h value for 0.508 mm diameter SMA wire was improved by 110 W m^{-2} K^{-1}. However, when compared to still air cooling, the h value increased by 6.5 times for 0.1524 mm diameter SMA wire and 8.9 times for 0.508 mm diameter SMA wire. Although this is a significant improvement in the values of coefficient of heat transfer, the oil cooling is incorporated with certain limitations, which include sealing complexity to avoid seepage of oil, also in certain conditions, the viscosity of oil may provide the resistance to SMA motion. The authors later characterized the SMA actuator in thermal grease. It was found that the value of h for 0.508 mm diameter SMA wire was 55% lower as compared to h value of 0.1524 mm diameter SMA wire when thermal grease was used as heat sink. The value of h was significantly higher in thermal grease as compared to the h values in mineral oil and air. For example, the value of h for 0.1524 mm diameter SMA wire was 4.3 times higher as compared to that in mineral oil and 28 times higher than that in still air for same diameter SMA wire. The cooling with distilled water produced better results and cooled off the SMA actuators in least time as compared to all other cooling media. The water quenching increased the value of h by 1.3 times for 0.1524 mm diameter SMA wire and 1.6 times for 0.508 mm diameter SMA wire as compared to h values in thermal grease. However, water cooling has certain costs. However, the major limitation is the boiling temperature of water, as the temperature will exceed 100°C, the water will start boiling; therefore, it is only applicable when the transformation temperature is lower, for example, in Flexinol® 70°C. For water, some special sealing arrangements are necessary. Also, the water circulation without a pump is difficult.

Tadesse et al. [36] conducted a series of tests on Flexinol® and Biometal® SMA actuators manufactured by Dynolloy, Inc and Toki Corporation, respectively. Each sample had 0.1 mm diameter and 100 mm long. Considering the actuation current limitations, the authors actuated the Flexinol® SMA actuator with 180 mA and Biometal® wire with 200 mA actuation current.

The authors tested the SMA samples in various cooling media including forced air at 0.3 m s^{-1} using a small computer fan, forced air cooling at 4.6 m s^{-1} using a compressor, thermal grease, solid heat sink and water quenching. However, the cooling time in ambient conditions was used as standard to compare the results of other cooling media.

http://dx.doi.org/10.5772/intechopen.69868

The SMA actuators cooled off in 1.1 second while let to cool in ambient air, whereas forced air cooling at 0.3 m s^{-1} improved the cooling time to 0.7 second. The high-speed air circulation cooled off the SMA actuators in about 0.3 second. Since the high-speed air circulation was achieved using a compressor, it is not practically applicable in miniature and weight conscious SMA systems. Solid heat sink was used in the form of aluminium tubes which were brought in contact with SMA actuators up on the power cut off to cool the SMA elements. The solid heat sink cooled the SMA actuators in 0.41 second. Solid heat sinking as proposed by the authors is not applicable in miniature applications, also it will require a close eye over the power shut down to bring the sink in contact with SMA actuator as soon as power supply is cut off. Water quenching cooled the SMA actuators in 0.2 second, which is significant reduction in the cooling time of SMAs as compared to ambient air cooling. However, the water circulation without a compressor is difficult, whereas water spray with a syringe is not practical in many applications including prosthesis, robotics and minimal invasive surgical applications. The thermal grease cooling was applied by filling it in a copper tube along with SMA actuators. The SMA actuator failed to contract while cooling with thermal grease. The author claimed that the reason for the failure in contraction was the fast dissipation of heat from the SMA actuator, which retained insufficient heat to cause a phase transformation in the actuator. However, in the proposed research, the SMA element was strained up to 4% when actuated with 810 mA actuation current, 410 mA actuation current also generated sufficient strain in the SMA actuator.

Russell and Gorbet [37] developed mobile heat sink with a two-wired differential type configuration. The authors used a 350 mm long SMA wire actuator of 0.3 mm diameter. The mechanism was arranged in such a way that the midpoint of the SMA actuator was anchored to a 6 mm diameter shaft, hence leaving 150 mm long SMA actuator on either sides of shaft. Furthermore, the heat sink, in a strip form, was attached to the shaft at the centre. As the wire contracted upon heating, it caused the shaft to rotate which simultaneously rotated the heat sink, attached to the shaft, towards the hot portion of the SMA wire, whose current supply was just disconnected. The reported SMA cooling mechanism is complex and is not applicable in conditions when smaller lengths of SMA actuator are used.

A comprehensive literature review is given in **Table 1**.

Sr. No.	Author	Cooling Media	Remarks
1	Loh et al. [32]	Silicone grease filled in copper tube	SMA Cooled off at 5°C per second, whereas heat loss at 1.75°C per second was observed which will result in more power consumption.
2	Loh et al. [33]	Stainless steel metal tube	Since the system is actuated with 50–70 V PWM, which is too high. Also, the metal tube, being rigid, will affect the system's flexibility in motion.
3	Taylor and Au [17]	Forced air cooling by a small fan	Although the proposed method is efficient to cool the SMA at faster rate, it is not suitable for miniature applications, as in catheters.

Sr. No.	Author	Cooling Media	Remarks
4	Cheng and Desai [34]	Water circulation	Water circulation produced the satisfactory results. However, the boiling temperature of water is core hindrance, also the water being a low viscous fluid will require special sealing arrangement.
5	Pathak et al. [35]	Still air	The cooling time increases with increase in SMA wire diameter.
		Forced air convection	Forced airflow can be achieved using a fan, which is not practical in miniature applications, like minimal invasive surgery.
		Mineral oil	Mineral oil produced a significant improvement in cooling time, as it was reduced up to 48% as compared ambient air cooling. However, in certain applications, oil sealing may be a problem.
		Thermal grease	Thermal grease reduced the cooling time by 55%. However, heat loss during actuation is a serious issue as reported by [6, 32].
		Water	Cooling with water produced best results amongst all other coolants. However, sealing to avoid leakage is core problem.
6	Tadesse et al. [36]	Forced air using computer fan	Airflow using a fan, which is not practical in miniature applications, like minimal invasive surgery. Also, special control algorithms may be required to control air speed.
		Forced air using compressors	The use of compressor is not applicable in miniature, biomedical weight conscious applications of SMAs.
		Thermal grease	The SMA actuator failed to contract due to rapid heat loss to the coolant i.e. thermal grease.
		Solid heat sink	Aluminium tubes, used as solid heat sink, were brought in contact with SMA actuator as power was cutoff. This will require a close look on power supply so that the heat sink may be brought in contact as soon as the power is cut off, or this will require complex control algorithms.
		Water	Cooling with water produced best results amongst all other coolants. However, sealing to avoid leakage is core problem and boiling temperature of water are core hindrances.
7	Russell and Gorbet [37]	Mobile heat sink with two-wire differential type configuration	The reported mechanism is complex and is not applicable with short SMA wires.

Table 1. Review of various cooling media.

5. Materials and methods

5.1. Experimental setup

A special purpose setup was developed to test the SMA actuators for various parameters. The experimental setup comprised of a laser displacement sensor, a load cell, a k-type thermocouple, a current transducer, an NI Elvis prototyping board, my RIO devices and power supply units to actuate the SMA actuator and to power the sensors. The experimental setup is shown in **Figure 3**.

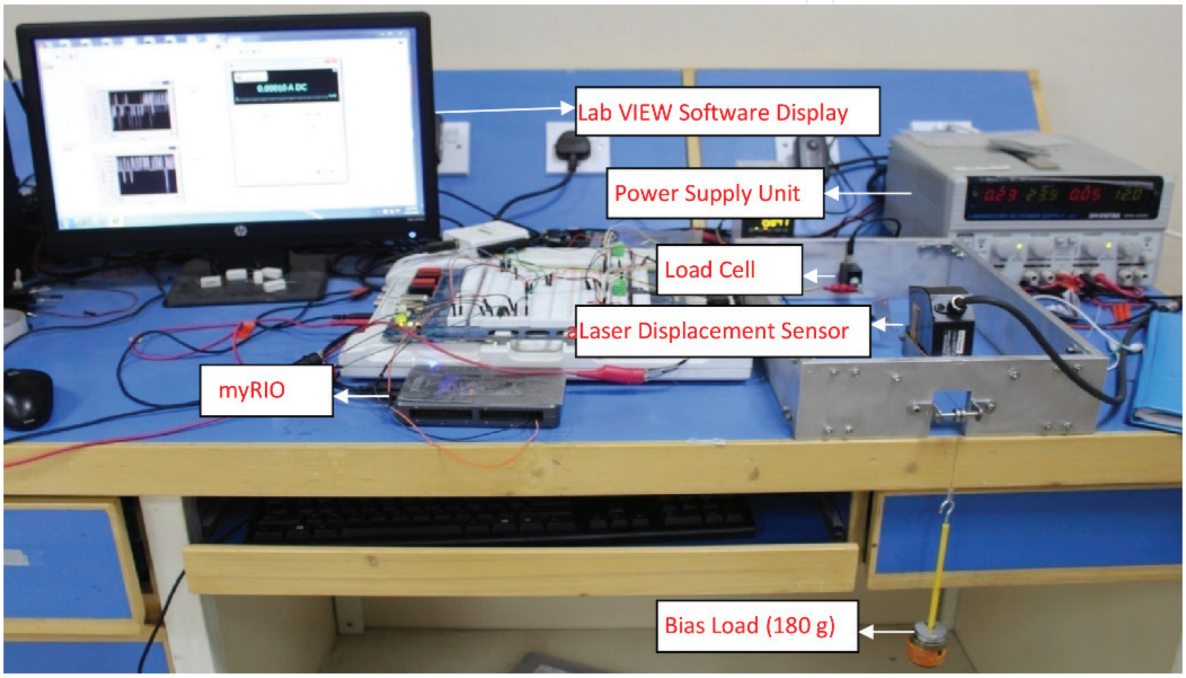

Figure 3. Experimental setup.

5.1.1. Sensors

The special-purpose experimental setup consisted of different sensors, including a laser displacement sensor to determine the contraction (i.e. strain) in the SMA actuators, a load sensor to determine the force exerted by SMA in lifting up the dead weight, a k-type thermocouple to measure the temperature of actuator and a current transducer to determine the current flow across the SMA actuator.

5.1.1.1. Laser displacement sensor

These are the non-contact sensors used to determine the displacement or deformation in case of SMA actuators. Due to high accuracy, these sensors are preferred over the traditionally used displacement sensors, like proximity sensors. In the presented research, the LK-G157 laser displacement sensor made by Keyence was used to detect any deformation, i.e. strain in the SMA actuators. This laser displacement sensor (LK-G157) is capable to measure the deformation when the object is within the range of 150 mm; however, it can measure a maximum of 40 mm displacement. It is provided with a red semiconductor laser which emits light of wavelength 655 nm.

5.1.1.2. Load cell

The tension produced in the SMA actuator while lifting dead weight was determined using a load sensor. Transducers Kit load cell model mdb 2.5 lb, having capacity to measure 2.5 lb, was used in this research.

5.1.1.3. Thermocouple

A close look at the temperature of the SMA actuator is necessary in order to avoid over heating of the SMA actuator, which can cause a permanent deformation. A fine gauge k-type thermocouple along with a MAX7785 amplifier was used to measure the temperature of the SMA actuators. Since the SMA wire diameter was very fine (i.e. 0.15 mm), the contact loss between SMA and the thermocouple was a serious issue, which is addressed by Ref. [38].

5.1.1.4. Current transducer

The strain in the SMA actuator is proportional to the amount of actuation current. An ACS 712 current transducer having analogue output was used to keep a close look on the amount of current being flowing through the SMA actuator.

5.1.2. Actuators

The presented work aims at developing the faster SMA actuators. A series of experiments were conducted on a high-temperature (90°C transformation temperature) Flexinol® SMA actuator having 0.15 mm diameter. The length of SMA actuator while testing in ambient air was 80 mm; however, the length of SMA actuator in heat sink was 90 mm. The Flexinol® SMA actuators can withstand a maximum strain of 8%, whereas 4% strain is considered to be safe for cyclic operations.

5.1.3. Tubing

In this research, the SMA actuator was run through the Polytetrafluoroethylene (PTFE) tube along with the coolant. The care was taken that SMA actuator was completely jacketed around with the coolant. PTFE tube, due to its favourable mechanical and chemical properties, was preferred over other tubing. Various chemical characteristics that make PTFE material superior are its resistance to corrosive reagents, non-solubility, long-term weatherability, non-adhesiveness and non-flammability, whereas its mechanical properties include stability at high temperatures, flexibility at low temperature and low coefficient of friction [39].

5.1.4. Coolants

In order to achieve faster cooling, the PTFE tube was initially filled with high-temperature synthetic base grease (NLGI-3). Later, the tests were conducted with the PTFE tube filled with oil (Shell Helix Hx3 20W-50 Mobil Oil).

5.2. Methods

The SMA actuator was actuated using Joule heating method, with different level of actuation current in ambient air, grease and oil. In Joule heating, the SMA element is heated taking advantage of the resistance offered by it to the passage of electrical current. When the current passes through the SMA element, power losses are produced which in result heat the SMA actuator. This method of heating can be described by Eq. (2) (heating power).

$$P = I^2 R \tag{2}$$

Here,

P = Electrical power to heat the SMA actuator,

I = Current across actuator, measured in Ampere (A) and

R = Resistance offered by SMA actuator to the flow of current, measured in Ohm (Ω).

For experiments in ambient air, bare SMA actuator was used. Therefore, close look on the actuation current was necessary to avoid over heating of the actuator. The maximum current in ambient air tests was set as per given specification of the SMA actuator manufacturer. However, the SMA actuator was run through the PTFE tube while testing in grease and oil. PTFE material is flexible at low temperatures and is stable at high temperatures, also it offers less friction. However, during preparation for test, the sealing of the coolant, i.e. grease or oil inside the PTFE tube was a serious issue. This issue was later overcome by inserting a smaller diameter PTFE tube in the bottoms of the main PTFE tube, carrying the coolant and SMA actuator. Since grease and oil worked as heat sink, SMA actuator was tested at higher actuation currents with negligible chances of overheating. **Figure 4** shows the schematic diagram of the SMA actuator in PTFE tube along with the coolant.

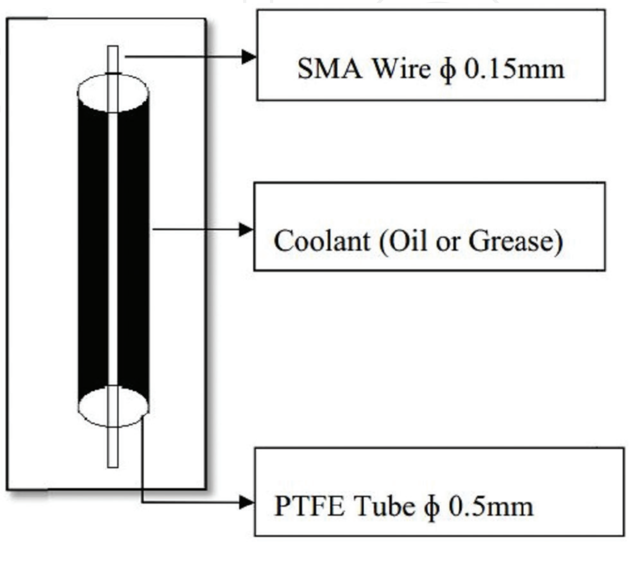

Figure 4. Proposed heat sink.

The SMA actuator was made to lift up a dead weight of 180 g, which induced 100 MPa stress in the SMA actuator. The data acquisition rate was set at 5 samples per second, which was sufficient to thoroughly examine the condition of SMA actuator during actuation and after the current supply was cutoff.

The thermal conductivity values of grease and oil are higher than the air (i.e. $\lambda_{OIL, GREASE} > \lambda_{AIR}$) as given in **Table 2**; therefore, the proposed heat sink will result in faster SMA cooling as compared to ambient air cooling.

Other factor affecting the cooling time is the surface area. Since the surface area of SMA is smaller than the surface area of PTFE tube (i.e. $A_{SMA} < A_{PTFE}$), the heat from the SMA will spread to the greater surface area of PTFE tube through the thermal conductive oil/grease, as shown in **Figure 5**.

Material	SMA	Teflon tubing	Thermal grease	Thermal oil	Air
Thermal conductivity (λ) in W m^{-1} K^{-1}	18 [3]	0.25 [40]	0.79 [41]	0.145 [40]	0.0257 [40]

Table 2. Thermal conductivity of different material.

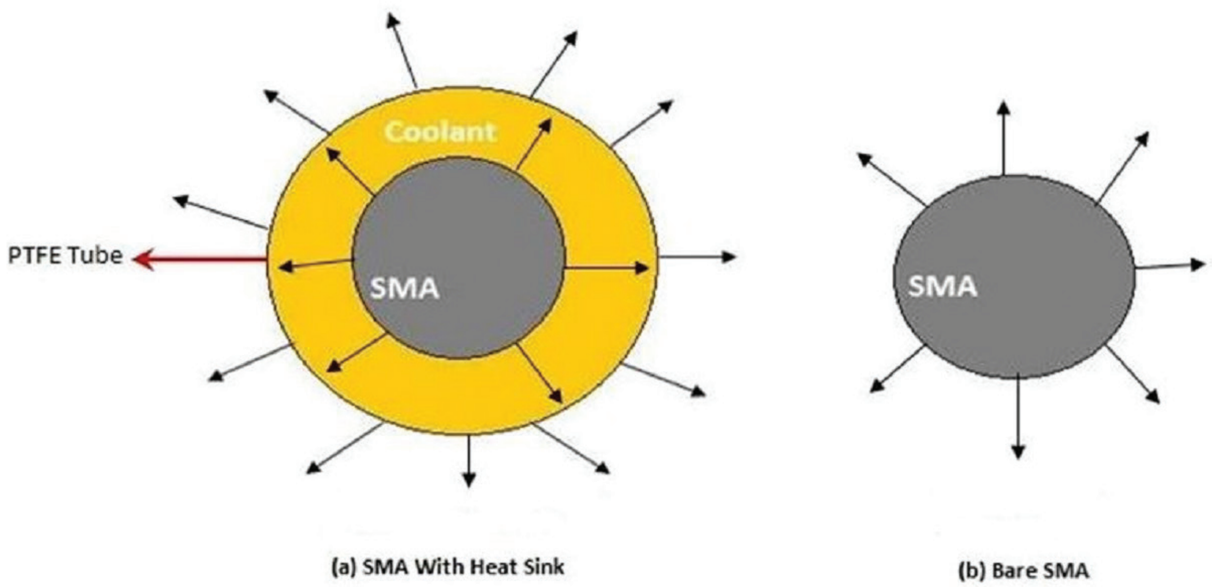

Figure 5. Area and heat dissipation model of (a) SMA with sink and (b) bare SMA.

6. Experiments and results

The SMA actuator was tested in ambient air, grease and oil, and time required by these cooling media was analysed. However, the time required to restore last 0.5% strain is not included, as it is not considered by the manufacturer. To assure the SMA properties, fresh specimen was used in each test. The strain induced in the SMA actuator is calculated by using Eq. (3) (strain induced in SMA actuator).

$$\%\ Strain = \frac{\Delta l}{l} \times 100 \tag{3}$$

Here,

Δl = Change in length of SMA actuator due to heating, taken in mm

l = Pre-deformed length of SMA actuator, taken in mm

6.1. Tests in ambient air

An 80 mm long bare SMA actuator specimen was tested in ambient air at 210, 310 and 410 mA actuation currents. The time for a cycle was set 10 seconds, of them 1 second for heating and remaining 9 seconds for relaxing of actuator. It was assured that SMA actuator should return to its original condition before the next cycle started. The response of SMA actuator in the ambient air actuation is given in **Figure 6**.

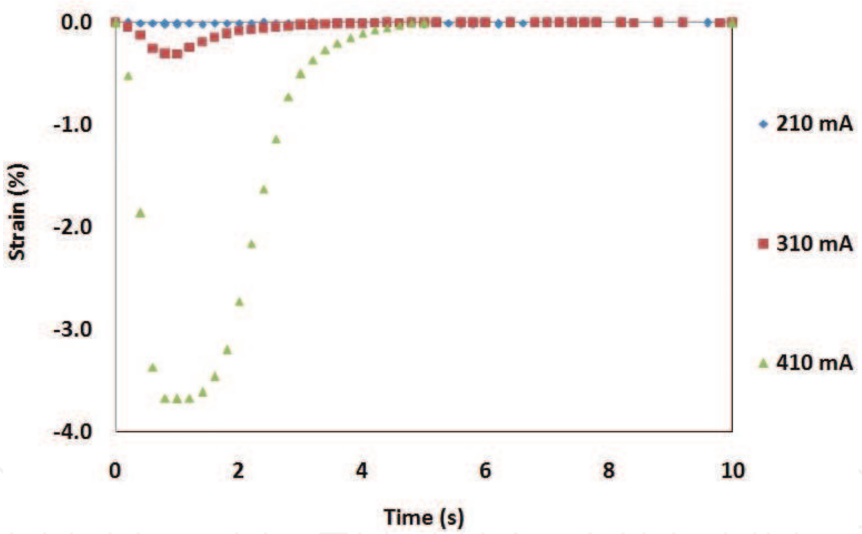

Figure 6. SMA actuator response in ambient air.

The negative sign on vertical axis in **Figure 6** shows the contraction in SMA actuator. It was found that heat energy produced at 210 mA heating current was too small to transform the SMA from martensite to austenite, hence resulting in negligible strain. When SMA actuator was actuated with 310 mA actuation current in ambient air, it could only be strained by 0.311%. This amount of strain is too small to be considered for any practical applications. The reason for small strain was the insufficient heat to cause a crystal rearrangement in the crystalline structure of the SMA. However, when SMA actuator was heated with 410 mA actuation current, a strain of 3.68%, i.e. 3 mm of contraction in SMA actuator was observed. This amount of strain is sufficient for many applications including minimal invasive surgery and other robotic applications. Upon the cutoff of power supply, the wire relaxed in 2 seconds. In such circumstances, the SMA actuator will have the working frequency of 0.333 Hz.

6.2. Tests in grease

For tests in grease, 90 mm long SMA actuator specimen was passed through an 80 mm long grease-filled PTFE tube. Being surrounded with grease, the chances of overheating were minimum; therefore, SMA actuator was actuated for 2 seconds as well. The SMA actuator sample was actuated with 210, 310, 410, 500, 615 and 720 mA for 1 and 2 seconds, whereas 810 mA actuation current was supplied for 1 second only.

6.2.1. One second actuation in grease

The SMA actuator specimen in grease-filled PTFE tube was actuated for 1 second at 210, 310, 410, 500, 615, 720 and 810 mA actuation currents. The time for a cycle was set 10 seconds, of them 1 second for heating and remaining 9 seconds for relaxing of actuator. It was assured that SMA could fully recover its initial form before the next cycle starts. **Figure 7** shows the response of SMA against 1 second actuation in grease.

Negative sign on the vertical axis in **Figure 7** shows contraction in the SMA actuator against the actuation.

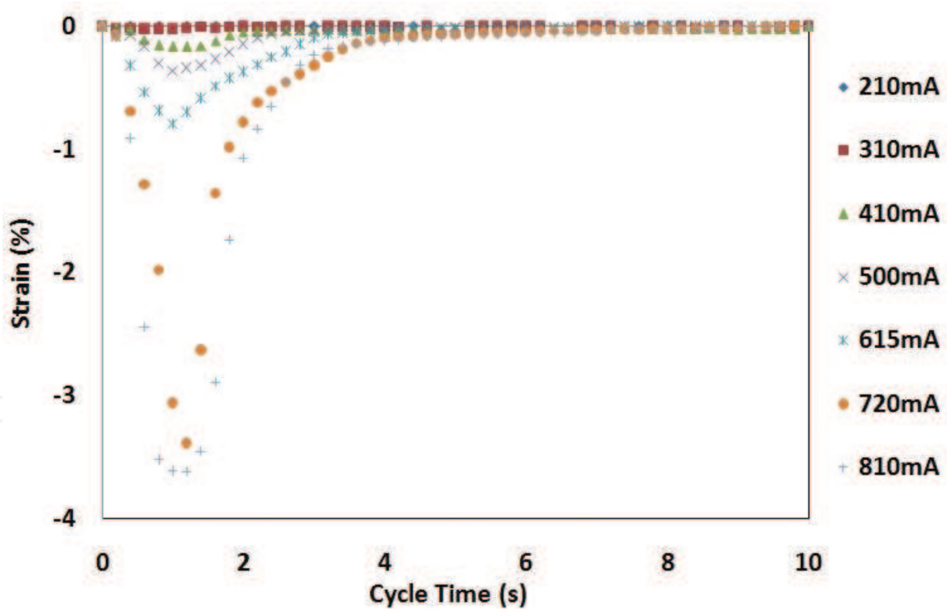

Figure 7. SMA actuator response against 1 second actuation in grease.

It can be observed that no strain was induced in the SMA actuator at 210 mA actuation current. The heat produced during actuation at 210 mA actuation was too low to cause a phase transformation in the actuator. At 310 mA heating current, the SMA actuator was strained by 0.0167%, which is too small for any application of SMA as actuator. At 410 mA heating current, due to rapid loss of heat to the coolant, i.e. grease, during heating, little amount of strain was induced in the SMA actuator, as compared to that produced in ambient air cooling, when heated with same level of actuation current. The actuation current of 410 mA could strain the grease-cooled actuator by 0.167%, which is only 4.54% of the strain produced in the ambient air-cooled SMA actuator at same actuation current. As discussed in the previous portions that due to higher thermal conductivity of grease than that of air, the heat loss rate to the grease was higher. Other reason for the rapid heat loss was the greater surface area of grease-cooled actuator, as it also included PTFE tube. The 500 and 615 mA actuation current resulted to 0.3635 and 0.7921% strain, respectively. Dynolloy Inc, in their technical data sheet for Flexinol SMA actuators, does not consider the time required to restore last 0.5% strain [3]. Therefore, in the grease-cooled SMA actuators, the cooling time for smaller strains is not considered. The SMA actuator deformed up to 3.047 mm when heated with 720 mA actuation current, this will induce a strain of 3.4%. This amount of strain is enough for SMAs to be applied as actuators in several applications like robotics, systems for drug delivery, catheters, etc. The SMA actuator cooled in 1.2 seconds. Sufficient quantity of heat was induced in the SMA to cause a phase transformation, when actuated with 810 mA actuation current. The heating was too fast for grease to absorb during actuation, due to which significant amount of heat was available inside the system to heat the SMA wire and cause a phase transformation. The 810 mA actuation current expanded the SMA actuator by 3.257 mm, resulting to 3.62% strain. However, the wire cooled off in 1.4 seconds, which is 30% improvement in cooling time as compared to that in ambient air. It should be noted that SMA actuator was strained by 3.68% when actuated with 410 mA actuation current in ambient air and recovered in 2 seconds.

6.2.2. Two seconds actuation in grease

The grease-cooled SMA actuators were actuated for 2 seconds with 210, 310, 410, 500, 615 and 720 mA actuation currents. These tests will help understand the effect of actuation time on the cooling efficiency of a heat sink. In these tests, the time for a cycle was set 10 seconds, of them 2 seconds for heating and remaining 8 seconds for relaxing of SMA actuator, in order to be assured that SMA fully recovers its pre-deformed shape and form before the next cycle starts. **Figure 8** shows the response of grease-cooled SMA actuator when actuated for 2 seconds at different actuation currents.

The negative sign on vertical axis represents contraction in SMA actuator, which is caused by heating.

It was observed that 210 mA actuation could not result in any deformation in SMA actuator, whereas a negligible amount of strain, about 0.04%, was observed in the SMA actuator at 310 mA actuation current. The heat energy produced by 210 and 310 mA actuation currents was too low to cause any phase transformation in the actuators.

When heated with 410 and 500 mA actuation currents, the SMA wire was strained by 0.35 and 0.6%, respectively. Because of rapid heat loss to the grease during heating, insufficient quantity of heat remained inside the SMA actuator to cause a complete phase transformation from martensite to the austenite. Whereas heating with 615 mA actuation current was sufficient to cause a significant amount of phase transformation in the SMA actuator. This could strain the actuator up to 3.2%, which is around four times higher than the strain produced by same level of actuation current when supplied for 1 second. The SMA wire actuator cooled off in 2.5 seconds, which is too high. The SMA actuator

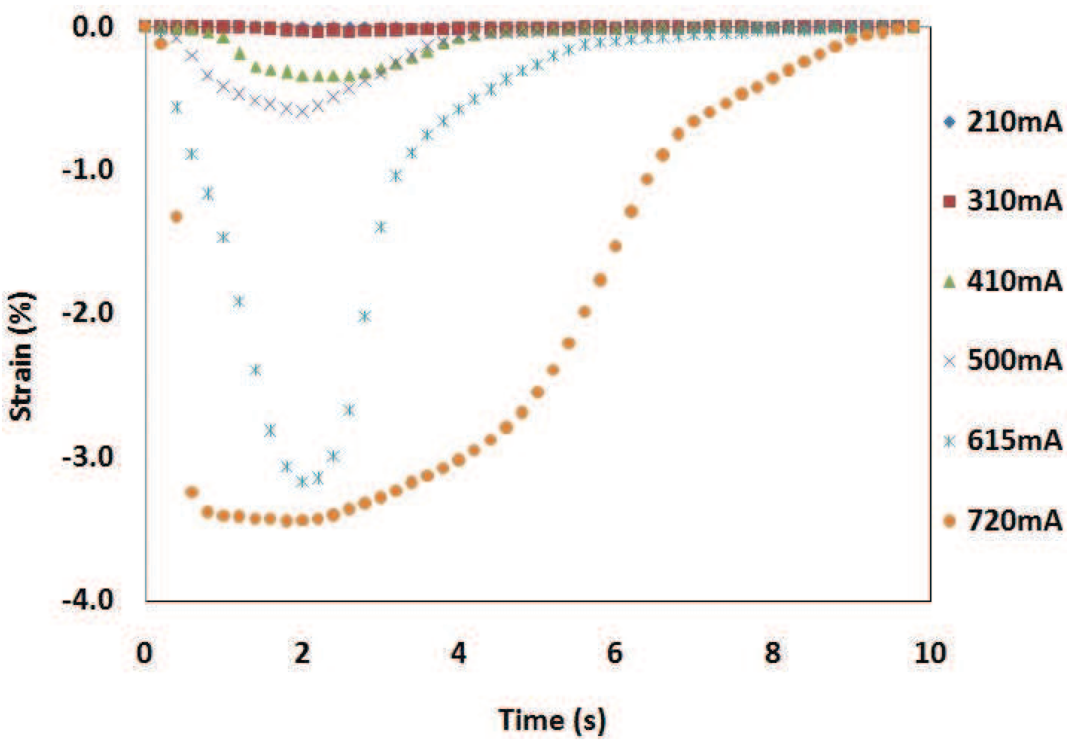

Figure 8. SMA actuator response against 2 seconds actuation in grease.

contracted up to 3.1 mm when heated with 720 mA actuation current supplied for 2 seconds. This resulted in 3.44% strain in SMA actuator, which is nearly equivalent to the strain produced with similar amount of actuation current when supplied for 1 second. However, the SMA wire cooled off in 6 seconds, which is five times greater than that required in 1 second actuation at same level of actuation current. This increase in cooling time shows that the efficiency of grease is affected with increasing heating time, especially at high actuation currents.

6.3. Tests in oil

To find out the effect of oil on SMA actuator cooling time, a 90 mm long SMA actuator specimen was run through an 80 mm long PTFE tube. The SMA actuator was heated with 210, 310, 410, 500, 615 and 720 mA current supplied for 1 and 2 seconds, whereas 810 mA actuation current was supplied for 1 second only.

6.3.1. One second actuation in oil

The SMA actuator specimen in oil-filled PTFE tube was actuated for 1 second at 210, 310, 410, 500, 615, 720 and 810 mA actuation currents. The time for a cycle was set 10 seconds, of them 1 second for heating and remaining 9 seconds for relaxing of SMA actuator. It was assured that SMA could fully recover its initial form before the next cycle starts. **Figure 9** shows the response of SMA against 1 second actuation in oil.

It was observed that 210 mA did not result in any strain in the SMA actuator; however, negligible strain in SMA actuator was observed at 310 and 410 mA actuation currents due to

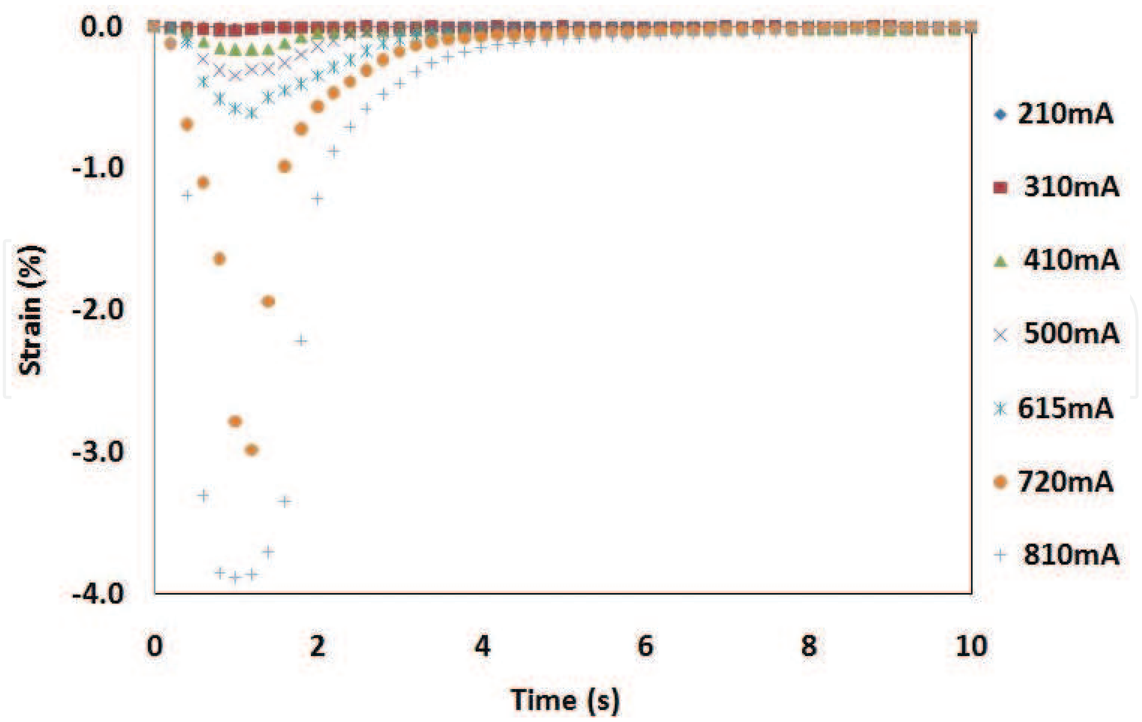

Figure 9. SMA actuator response against 1 second actuation in oil.

significant amount of heat loss to the oil during actuation. At 500 and 615 mA actuations, the SMA actuators strained by only 0.3472 and 0.6076%, respectively, due to insufficient amount of heat to cause phase transformation.

The 720 mA actuation current could produce sufficient heat to cause the phase transformation in the oil-covered SMA actuator. The 720 mA strained the SMA actuator up to 3%, producing 2.685 mm stroke length, which is sufficient for many SMA applications including catheters and latches and micro robots. The SMA actuator relaxed in 1 second hence capable to give 0.5 Hz frequency. While actuated with 810 mA current supply, the SMA was deformed by 3.5 mm, inducing 3.9%, which is 0.28% more than that produced with same actuation current in grease-cooled actuator. However, the cooling time required for SMA actuator was found to be 1.6 seconds.

6.3.2. Two seconds actuation in oil

The oil-cooled SMA actuators were actuated for 2 seconds with 210, 310, 410, 500, 615 and 720 mA actuation currents. SMA actuator heating for 2 seconds at various actuation currents will help understand the SMA behaviour against higher actuation times. These tests will also help understand the effect of actuation time on the cooling efficiency of a heat sink. In these set of tests, the time for a cycle was set 10 seconds, of them 2 seconds for heating and remaining 8 seconds for relaxing of SMA actuator. **Figure 10** shows the response of oil-cooled SMA actuator when actuated for 2 seconds at different actuation currents.

The negative sign on vertical axis in **Figure 10** denotes the shrinking in SMA actuator produced by heating.

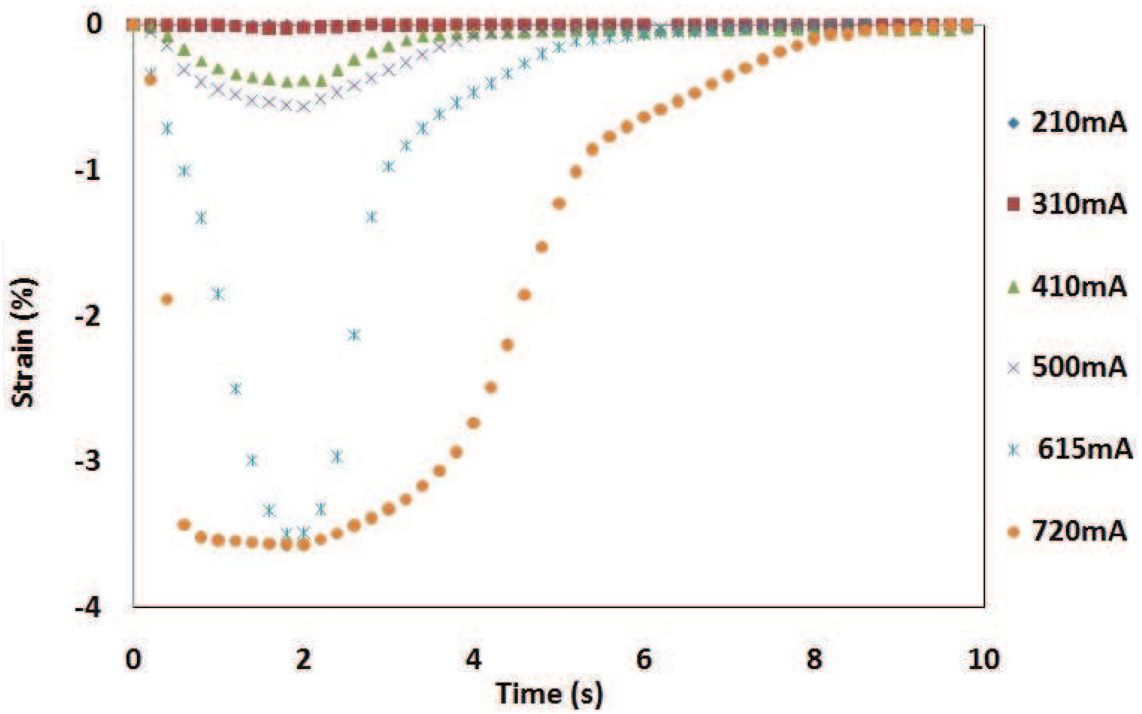

Figure 10. SMA actuator response against 2 seconds actuation in oil.

At 210 mA actuation current, no deformation in the SMA actuator was observed hence no strain in the SMA was induced, whereas negligible strain equal to 0.027% was observed at 310 mA actuation current. When actuated with 410 and 500 mA actuation currents, little strain equal to 0.4 and 0.56%, respectively, was observed. The observed quantity of strain is too small to for any real-time application of SMAs as actuators. However, 615 mA actuation current resulted in 3.5% strain in SMA, which is adequate for a number of real-world applications. The SMA specimen relaxed in 2 seconds, hence capable to give 0.33 Hz frequency. The SMA actuator contracted up to 3.213 mm, hence inducing 3.57% strain in the actuator, when heated with 720 mA actuation current. The actuator cooled off in 4.4 seconds. However, 410 mA actuation current in ambient air produced same amount of strain in the SMA actuator, whereas the wire had cooled off in 2 seconds, which is only 45.45% of cooling time required by SMA actuator when heated with 720 mA actuation current for 2 seconds in oil. The reason for the increase in cooling time is that the rejection of considerable amount of heat to the oil, which increased the temperature of oil, hence reducing the heat flow rate from actuator to the oil. It is general consideration that the heat transfer rate is proportional to difference of temperature between the two mediums.

7. Conclusions

From the results, it is derived that at same level of actuation current, grease- and oil-cooled SMA actuators underwent smaller strain as compared to the strain produced in ambient air cooling. The maximum heating current in ambient air was 410 mA, which strained the SMA actuator by 3.68%; however, the wire relaxed in 2 seconds, whereas an equivalent amount of strain in grease-cooled actuators was produced at 720 and 810 mA heating currents, and SMA actuators relaxed in 1.2 and 1.4 seconds, respectively, which is 40 and 30% improvement in cooling time of SMA as compared to that in ambient air. When actuated for 2 seconds in grease at 720 mA current supply, the actuator strained by 3.4% but recovered in 6 seconds, which is five times higher than the cooling time observed against 1 second actuation at 720 mA current in grease. Similarly, oil-cooled actuators produced considerable strain against 720 and 810 mA actuation current when heated for 1 second. The cooling times in this case were 1 and 1.6 seconds, respectively. Like grease-cooled actuators, the oil-cooled actuators required long cooling time against 2 seconds actuations, as the temperature of coolants, i.e. grease or oil was too high to efficiently absorb the heat. However, in case of ambient air cooling, close watch over the temperature of SMA is compulsory to prevent overheating which is likely to cause a permanent deformation in the actuator. However, in grease and oil cooling, the heat was rapidly being rejected to the coolant (i.e. grease or oil); therefore, likelihood of overheating of the SMA actuator is less. From the results and discussions sections, it can be observed that the oil-cooled actuator produced linear response, whereas the response of grease-cooled SMA actuator fluctuated at various points. The oil-cooled actuators produced more stroke length as compared to grease-cooled actuators and cooled off in less time. Therefore, for more strain, less cooling time, linear behaviour and safe actuation, the oil cooling is suggested over grease and ambient air cooling.

The presented research also reveals that increasing the actuation time also results in increased cooling time with no significant effect on the stroke length (i.e. strain). Therefore, it is further concluded that rather than increasing the heating duration with smaller magnitude currents, the magnitude of the heating current should be increased in order to avoid the heating of the sink.

Author details

Atta Muhammad Nizamani[1]*, Jawaid Daudpoto[1] and Muhammad Ali Nizamani[2]

*Address all correspondence to: attam.nizamani@gmail.com

1 Mehran University of Engineering and Technology, Jamshoro, Pakistan

2 Isra University, Hyderabad, Pakistan

References

[1] Ölander A. An electrochemical investigation of solid cadmium-gold alloys. Journal of the American Chemical Society. 1932;**54**:3819-3833

[2] Featherstone R, Teh YH. "Improving the Speed of Shape Memory Alloy Actuators by Faster Electrical Heating." Experimental Robotics IX, Springer (2006): 67-76. https://link.springer.com/chapter/10.1007%2F11552246_7?LI=true

[3] Dynalloy I. Technical Characteristics of Flexinol Actuator Wires. Dyanalloy Inc. Tustin, CA: 2011. www.dynalloy.com/pdfs/TCF1140.pdf

[4] Daudpoto, Jawaid, Ali Asghar Memon, and Imtiaz Hussain. "Actuation Characteristics of 0.15 Mm Diameter Flexinol® and Biometal® Wire Actuators for Robotic Applications." Mehran University of Research Journal of Engineering and Tecnology 32 (2013). Print.

[5] Lara-Quintanilla A, Bersee HE. A study on the contraction and cooling times of actively cooled shape memory alloy wires. Journal of Intelligent Material Systems and Structures 27.3 (2016): 403-17

[6] Nizamani, AM, J. Daudpoto, and MA Soomro. "Improving Cycle Time of Ni-Ti Shape Memory Alloy Actuators Using a Novel Cooling Technique." Sindh University Research Journal-SURJ (Science Series) 48.4D (2016), p 161-164

[7] Ikuta K. Micro/miniature shape memory alloy actuator. In: Proceedings, 1990 IEEE International Conference on Robotics and Automation, 1990; 13-18 May 1990; Cincinnati, Ohio, United States of America. IEEE; 1990. pp. 2156-2161

[8] Jani JM, Leary M, Subic A, Gibson MA. A review of shape memory alloy research, applications and opportunities. Materials & Design. 2014;**56**:1078-1113

[9] Butera F, Coda A, Vergani G, SpA SG. Shape memory actuators for automotive applications. Nanotec IT newsletter. Roma: AIRI/Nanotec IT; 2007. pp. 12-16

[10] Jani JM, Leary M, Subic A. Shape memory alloys in automotive applications. Applied Mechanics & Materials. 2014;**663**:248-253

[11] Zhong Z, Yeong C. Development of a gripper using SMA wire. Sensors and Actuators A: Physical. 2006;**126**:375-381

[12] Esfahani ET. Developing an Active Ankle foot Orthosis based on Shape Memory Alloys. The University of Toledo, Ohio, USA; 2007

[13] Copaci D, Flores A, Rueda F, Alguacil I, Blanco D, Moreno L. Wearable elbow exoskeleton actuated with shape memory alloy. In: Converging Clinical and Engineering Research on Neurorehabilitation II. Springer; 2017. pp. 477-481. Proceedings of the 3rd International Conference on NeuroRehabilitation (ICNR2016), October 18-21, 2016, Segovia, Spain. https://link.springer.com/chapter/10.1007/978-3-319-46669-9_79

[14] Rossi C, Colorado J, Coral W, Barrientos A. Bending continuous structures with SMAs: A novel robotic fish design. Bioinspiration & Biomimetics. 2011;**6**:045005

[15] Gaissert N, Mugrauer R, Mugrauer G, Jebens A, Jebens K, Knubben EM. Inventing a micro aerial vehicle inspired by the mechanics of dragonfly flight. 14th International Conference Towards Autonomous Robotic Systems,TAROS 2013, Oxford, UK, August 28--30, 2013. pp. 90-100. Springer, ISBN: 978-3-662-43645-5

[16] Coral Cuellar W, Rossi C, Colorado Montaño J, Barrientos Cruz A. SMA-Based MuscleLike Actuation in Biologically Inspired Robots: A State of the Art Review. Intech; 2012

[17] Taylor F, Au C. Forced air cooling of shape memory alloy actuators for a prosthetic hand. Journal of Computing and Information Science in Engineering (2016):16(4), 041004 (Nov 07, 2016) (5 pages) Paper No: JCISE-16-1051; doi:10.1115/1.4033233, Received January 29, 2016; Revised March 16, 2016 https://computingengineering.asmedigitalcollection.asme.org/article.aspx?articleID=2511361

[18] Morgan N. Medical shape memory alloy applications—the market and its products. Materials Science and Engineering: A. 2004;**378**:16-23

[19] Datla NV, Honarvar M, Nguyen TM, Konh B, Darvish K, Yu Y, et al. Towards a nitinol actuator for an active surgical needle. In: ASME 2012 Conference on Smart Materials, Adaptive Structures and Intelligent Systems; 19-21 September 2012; Georgia, USA. 2012. pp. 265-269. http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1720812

[20] Guo S, Fukuda T, Kosuge K, Arai F, Oguro K, Negoro M. Micro catheter system with active guide wire-structure, experimental results and characteristic evaluation of active guide wire catheter using ICPF actuator. In: Proceedings, 1994 5th International Symposium on Micro Machine and Human Science; 2-4 October 1994; Cincinnati, OH, USA. IEEE; 1994. p. 191

[21] Reynaerts D, Peirs J, Van Brussel H. Design of a SMA-actuated implantable drug delivery system. In: MHS'95, Proceedings of the 6th International Symposium on Micro Machine and Human Science, 1995; 4-6 October 1995; Nagoya, Japan. IEEE; 1995. p. 111

[22] Potnuru A, Wu L, Tadesse Y. Artifiial heart for humanoid robot. Proc. SPIE 9056, Electroactive Polymer Actuators and Devices (EAPAD) 2014, 90562F (March 8, 2014); San Diego, California, USA doi:10.1117/12.2045289; http://dx.doi.org/10.1117/12.2045289

[23] Duerig T, Pelton A, Stöckel D. An overview of nitinol medical applications. Materials Science and Engineering: A. 1999;**273**:149-160

[24] Kudva JN. Overview of the DARPA smart wing project. Journal of Intelligent Material Systems and Structures. 2004;**15**:261-267

[25] Quan D, Hai X. Shape memory alloy in various aviation field. Procedia Engineering. 2015;**99**:1241-1246

[26] James H. Mabe ; Frederick T. Calkins and Mehmet B. Alkislar "Variable area jet nozzle using shape memory alloy actuators in an antagonistic design", Proc. SPIE 6930, Industrial and Commercial Applications of Smart Structures Technologies 2008, San Diego, California 69300T (March 19, 2008); doi:10.1117/12.776816; http://dx.doi.org/10.1117/12.776816

[27] Lucy MH, et al. "Report on Alternative Devices to Pyrotechnics on Spacecraft." (1996). 10th Annual AIAA/USU Conference on Small Satellites; 17-19 Sep. 1996; Logan, UT; United States. https://ntrs.nasa.gov/search.jsp?R=19960054342

[28] Allegranza, C., Gaillard, L., Le Letty, R., Patti, S., Scolamiero, L., & Toso, M. (2014, March). Actuators for Space Applications: State of the Art and New Technologies.

Actuator. In the proceedings of the 14th International Conference on New Actuators, Messe Bremen WFB Wirtschaftsförderung Bremen GmbH, Bremen, Germany. 742 p, ISBN 978-3-933339-22-5 . Proceedings available online at, http://www.actuator.de/userfiles/File/ACTUATOR_14/ACTUATOR_2014_ordform.pdf

[29] Olivier J. Godard ; Magdalini Z. Lagoudas and Dimitris C. Lagoudas "Design of space systems using shape memory alloys", Proc. SPIE 5056, Smart Structures and Materials 2003: Smart Structures and Integrated Systems, 545 (August 5, 2003) Volume 5056, San Diego, California, USA. http://dx.doi.org/10.1117/12.483469

[30] Hartl DJ, Lagoudas DC. Aerospace applications of shape memory alloys. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2007; **221**:535-552

[31] Sonawane NS, Thangavelautham J. Precision pointing of antennas in space using arrays of shape memory alloy based linear actuators. arXiv preprint arXiv:1701.07561, 2017

[32] Loh CS, Yokoi H, Arai T. Natural heat-sinking control method for high-speed actuation of the SMA. International Journal of Advanced Robotic Systems. 2006;**3**:42

[33] Loh CS, Yokoi H, Arai T. New shape memory alloy actuator: Design and application in the prosthetic hand. In: IEEE-EMBS 2005. 27th Annual International Conference of the Engineering in Medicine and Biology Society, 2005; 17-18 January 2006; Shanghai, China. IEEE; 2006. pp. 6900-6903

[34] Cheng SS, Desai JP. Towards high frequency actuation of SMA spring for the neurosurgical robot-MINIR-II. In: 2015 IEEE International Conference on Robotics and Automation. (ICRA); 26-30 May 2015; Seattle, Washington, USA. IEEE; 2015. pp. 2580-2585

[35] Pathak A, Brei D, Luntz J. Transformation strain based method for characterization of convective heat transfer from shape memory alloy wires. Smart Materials and Structures. 2010;**19**:035005

[36] Tadesse Y, Thayer N, Priya S. Tailoring the response time of shape memory alloy wires through active cooling and pre-stress. Journal of Intelligent Material Systems and Structures. 2010;**21**:19-40

[37] Russell RA, Gorbet RB. Improving the response of SMA actuators. In: Proceedings, 1995 IEEE International Conference on Robotics and Automation, 1995; 21-27 May 1995; Nagoya, Japan. IEEE; 1995. pp. 2299-2304

[38] Soomro, MA, J. Daudpoto, and AM Nizamani. "Design, Development and Validation of an Experimental Test Bed for SMA Actuators." Sindh University Research Journal-SURJ (Science Series) 48.4D (2016). p 39-44

[39] Teflon P, Resin PF. Properties Handbook. Washington: DuPont Fluoroproducts; 1996

[40] Box ET. Thermal Conductivity of Materials and Gases [Internet]. Available from: http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html [Accessed: 25 April 2016]

[41] Thermalloy. Thermal Greases [Internet]. Available from: htt://www.aavid.com/productgroup/interface/greases [Accessed: 25 April 2016]