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Effect of Polydimethylsiloxane (PDMS) Coating on the Behavior of Shape Memory Alloy (SMA) Actuator

N. A. Jumat, E. J. Abdullah, N. Mazlan

Abstract: ***Shape Memory Alloy (SMA) is a memory metal where it is able to return its initial shape after deformation. SMA will contract when heated and return to its original shape. Thus, SMA can be used as an actuator and it is simpler compared to motor (servo) and piezoelectric. SMA is considered as clean technology as it requires small amount of power to produce large actuation. SMA wire is heated by joule heating when applying an electric current through it, resulting in contraction. SMA is also lightweight, making it an ideal actuator for a flapping wing micro air vehicle (MAV) design that has weight and space constraints. However, the SMA's behavior is nonlinear and the cooling rate is slow. A feedback control system is required to produce accurate actuation of the SMA and a cooling method needs to be included in the design. In this research work, polydimethylsiloxane (PDMS) was used to improve the cooling of the SMA actuator. PDMS is a flexible for wide range of temperature (-40^{o}C to 400^{o}C) which ideally can be used for SMA with temperature reaching up to 70^{p}C during heating. The behavior of SMA with and without PDMS were analyzed to investigate the effects on the feedback response of the SMA actuator. It was found that the PDMS coating increased efficiency of the SMA actuation by improving the time response and reducing the overshoot of the response of the SMA actuator.***

Index Terms**:** ***Keywords: PDMS; SMA; Flapping wing; Actuator.***

I. INTRODUCTION

Micro air vehicle is a small, portable flying vehicle that can be useful to various area. For example, micro aerial robots towards aerial interactivity, swarm-based operations that is sensitive or harmful surveillance zone, natural disaster assessment and even convoy escort. For all that, the fundamental aeromechanics behind the actuation system is yet to be understood where many researches on bio-inspired flight have been presented by looking at different birds and insect but it doesn’t have to translate to a set of theoretical model that can be applied on the actuation system for a flying MAV. Flapping wing has the potential to revolutionize MAV due to increased aerodynamics performance, improved maneuverability and hover capabilities but the characteristics must be properly understood[1]. Designers tend to imitate flapping flight of birds, bats and insects but the machines may differ in form, where they are usually built on the same scale as these flying creatures. Fixed and flapping wing concept have been explored in MAV technology. However, the flexible actuation system able to perform the asymmetric flapping wing actuation system needs to be develop which yield better performance that rigid or fixed wing because of the adaption in shape and delay to stall[1]. Once this has been established then only it can be successfully replicated by a flapping wing actuation system for MAV.

The main objective of this project is to flap a plate using SMA and to obtain the desired frequency and to determine the method of actuation for flaps. Motors are the easiest solution since many similar projects flapping wing design used motors, but they were discarded as an option given that there were known problems with using motors in an application with limited space. Nitinol wire or SMA is suggested as a possible actuation method since it had been used in similar applications with success[2]. The problem with using SMA is that not much was known about how to use SMA as an actuator. Also, many actuators using SMA as the method of actuation were incapable of holding loads. Early flight attempts or efforts are often taken as a combination of unconventional and recurrently failed experimentation, which lead to two viably tested approaches: fixed and rotary wing designs[3]. A significant advantage of flapping wing propulsion is that lift can be generated with little or no forward velocity and with small wing size and flapping wing has a greater capability to recover potential energy[3]. In this global energy crisis worldwide, SMA application can contribute in reducing energy consumption. In the work presented here, SMA is used as an actuator to flap the plate and the actuation system controlled using LabVIEW. Since SMA has a low cooling rate, PDMS was utilized to improve the cooling.

II. SMA ACTUATORS

Shape memory alloy (SMA) refer to that group of metallic materials that demonstrates the ability to return to its original shape or some previously defined shape when subjected to the appropriate thermal procedure[2]. SMA is based on nickel and titanium (NiTi) that available in wire, spring and plate form. There are two widely use that known as Flexinol (Dynalloy Inc., USA) and Biometal fiber (Toki Corporation, Japan). For this study, type of SMA use is from

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Flexinol (Dynalloy Inc., USA). Generally, these materials can be plastically deformed at some relatively low temperature and upon exposure to some higher temperature will return to their shape prior to the deformation. Materials that exhibit SMA only upon heating are referred as one-way shape memory. Some materials also undergo a change in shape upon re-cooling. These materials have a two-way shape memory. At high temperature, the behavior of the SMA become super-elastic[4]. Compared to motor or piezoelectric, SMA have various advantage such as high force to weight ratio, deploy simple current drive and operation. However, SMA is limited in application due to low operational frequency and narrow bandwidth. For the bandwidth, it is limited because of the time required for heating and cooling the actuator. Furthermore, the time response for SMA also depend on preload stress, load and amplitude of activation potential[5].

SMA may be further defined as one that yields thermos-elastic martensite. In this case, the alloy undergoes a martensite transformation of a type that allows the alloy to be deformed by a twinning mechanism below the transformation temperature. The deformation is then reverse when the twinned structure reverts upon heating to the parent phase. The martensitic transformation that occurs in the shape memory alloys yields a thermos-elastic martensite and develops from a high-temperature austenite phase with long-range order[6]. The martensite typically occurs as alternately sheared platelets, which seen as a herringbone structure when viewed metallographically. The transformation, although a first-order phase change, does not occur at a single temperature but over a range of temperatures that varies with each alloy system. Most of the transformation occurs over a relatively narrow temperature range, although the beginning and end of the transformation during heating or cooling extends over a much larger temperature range[7]. The transformation also exhibits hysteresis in that the trans-formation on heating and on cooling does not overlap.

A. SMA Application as an Actuator

There are numerous applications of shape memory alloy in aerospace. One of it is in fixed-wing aircraft and rotorcraft applications. Shape memory alloy applied specifically to propulsion systems and structural configurations where the most known pro-jects for fixed-wing are Smart Wing Project and Smart Aircraft and Marine Propulsion System (SAMPSON)[8]. For Smart Wing Project, where optimizing the performance of lifting bodies which divided into two parts, SMA wire tendons is used to actuate hingeless ailerons while SMA torque tube used to initiate spanwise wing twisting of a scale-down F-18[9]. In these applications, the SMAE is used to provide actuation via shape recovery occurs at a non-zero stress. For the SAMPSON Program demonstrated the usefulness of active materials in tailoring the inlet geometry and orientation of various propulsion systems. The experimental validation was performed on a full-scale F-15 inlet. At first, the wind tunnel testing was conducted at NASA Langley's high speed facility for antagonistic system where the SMA was set on opposite side. SMA is also used for spacecraft applications where usually SMA are applied to overcome the problem of low-shock release[10]. SMA is suited for use in low-shock release mechanisms since it can actuate slowly by gradual heating. SMA has been introduced to be used on both average size and micro size satellite for example Micro Sep-Nut[10]. Another use of SMA was actuated solar collector which utilized torsional elements that can modify its own shape to optimize performance[11]. In additional, SMA wire also use to actuate stepper motor for orientation of its solar flaps[12]. For Mars Pathfinder mission in 1997 which the mission use SMA actuator to rotate a dust cover from specific region of a solar cell, thus the protected and clean region of power output can be compare with the non-protected regions. From this mission, the negative effect of dust settling on the solar panel can be identify[12].

B. Control Technique

Temperature and stress that act on SMA can change the behavior and properties of the SMA. The transformation from different phases which are martensite and austenite, the transfer of heat, stress and temperature on the SMA are non-linear. This non-linear properties make it become complex to design the control system. Usually, the study on controlling SMA done by directly measure the temperature and strain of the SMA. The resistance of SMA changes according to the phase transformation that can be used as a feedback in order to control the SMA. However, the resistance of SMA is very low and most of the resistance feedback use SMA with length 22cm until 100cm[7] or use more than one SMA wire that connect in series to increase the resistance[6]. In order to control the SMA, few techniques can be used. Firstly, Pulsed Width Modulation (PWM) where it requires temperature feedback approach to control the radius of curvature of an arc-shaped SMA wire. Using temperature feedback can control the strain of the SMA wire. A PWM-based non-linear PID controller with a feed-forward heat transfer model is proposed to utilize temperature-feedback for tracking a desired temperature trajectory[13]. Besides, PWM is an efficient way for SMA actuator since it is easy to be implemented in any software or hardware for example LabVIEW and Matlab.

Then, the increases in temperature of the SMA because of the increases in error for the constant gain controller. This phenomenon occur due to SMA wire temperature increase, the heat loss also increases same goes to nonlinear dynamics of the SMA actuator[13]. Different current inputs were applied to the SMA wire to ensure good thermal contact between the resistance temperature detector (RTD) sensor and SMA wire. Another method, if faster electric heating where resistance was used as a form of temperature measurement and the maximum safe heating current was designed to prevent overheating. The cooling rate can be increased by various ways including forced-air cooling, oil or water cooling and using thinner SMA wire[14]. There are two-stage relay controller for antagonistic pairs of SMA and incorporated the rapid-heating. Forward and reverse SMA elements pulled in the positive and negative directions, respectively as measured by the position sensor. Rapid heating mechanism substantially improves the speed but the tracking accuracy is poor because of the large limit cycles.

From the development equations for SMA actuator, which basically from physical process and control strategies using the prototype model, there were three equations[15]. This equation can be used for controlling the behavior of the SMA. The equations as follows. The (1) equation is get from the linearized non-linear equations that describe the Joule heating convectional, where *m* is the mass per unit length, c_p is the specific heat capacity, *V* is the voltage that applied across the SMA wire, *R* is the resistance of the SMA wire which for per unit length, *h* is the coefficient of convectional cooling, *A* is the circumference area of cooling, *d* is the diameter of SMA wire, *T* is the reading temperature and T_a is the ambient temperature.

h is assume have the characteristic of second-order polynomial that enhance the rate of convection at higher temperature as in equation (2).

$$\dot{T} = \frac{1}{mc_p}\left[\frac{V^2}{R} - hA(T - T_a)\right] \qquad (1)$$

$$h = h_0 + h_2T^2 \qquad (2)$$

For the heating and cooling process, the equations are (3) and (4) respectively where ε is the fraction of the phases, ε_m and ε_a are the fraction of martensite phase and austenite respectively, *T* is the reading temperature, T_{f_a} and T_{f_m} are the transition temperature from martensite to austenite and transition temperature from austenite to martensite respectively, σ_a and σ_m is the indicator of the range of temperature around the transition temperature, σ is the stress, K_a is the stress curve-fitting parameter that obtained from the loading plateau of the stress-strain with no change of temperature while K_m is the stress curve-fitting parameter that obtained from the unloading part of the stress-strain. Both indicate the response of the SMA wire application of external stress.

$$\varepsilon = \frac{\varepsilon^2}{\varepsilon_m}\left[exp\left(\frac{T_{fa} - T}{\sigma_a} + K_a\sigma\right)\right]\left[\frac{\dot{T}}{\sigma_a} - K_a\dot{\sigma}\right] \qquad (3)$$

$$\varepsilon = \frac{\varepsilon^2}{\varepsilon_a}\left[exp\left(\frac{T_{fm} - T}{\sigma_m} + K_m\sigma\right)\right]\left[\frac{\dot{T}}{\sigma_m} - K_m\dot{\sigma}\right] \qquad (4)$$

III. COOLING FOR SMA ACTUATORS

For active cooling technique, a SMA wire can be heated in different manners, although the most commonly used way is Joule heating due to its high efficiency. Depending on the application, the SMA wires can be passively or actively cooled. SMA wires are passively cooled when they release heat to the surrounding environment by conduction, convection or both without the existence of a system that controls the cooling rate of the wires. Conversely, SMA wires are actively cooled when a system controls and increases the cooling rate of the SMA, thus increasing its actuation frequency. The difference between the physics behind the heating and the cooling processes makes the contraction and the cooling times notably different. The cooling time is noticeably larger than the contraction time on SMA wires and, therefore, it is the limiting factor in terms of attainable actuation frequency.

A. Polydimethylsiloxane (PDMS)

In recent time polydimethylsiloxane (PDMS), an attractive choice for realization of various devices are explored for biomedical, mechanical and aerospace applications. PDMS are made up from carbon, hydrogen, silicon and oxygen that make it belong to group silicone[16]. However, its properties vary with its composition. PDMS is a clean material since it is non-toxic, hydrophobic is very high and not bio-accumulate[16]. SU-8 'fiber' one of the finest MAV using PDMS on its wings that mimicking insects wing through advanced microelectromechanical system(MEMS)[17]. PDMS is thermally stable throughout the entire range of temperature during actuation of the SMA wires and presents good thermomechanical properties that make it suitable for use in the soft actuators even though it is not the best choice of material to optimize cooling conditions[18].

IV. EXPERIMENTAL SETUP

Experiment was conducted to test and compare the behavior of the SMA when coated with PDMS and SMA without PDMS. The specifications of the SMA wire used is as shown in Table I. The length and diameter of the SMA wire was 6.5cm and 0.00035cm respectively.

Table I: Specifications of SMA wire

Parameter	**Value**
Mass per unit length (m in kg m^{-1})	4.54×10^{-4}
Specific heat capacity (c_p in J kg^{-1} K^{-1})	320
Resistance per unit length (R in Ω m^{-1})	12.2
Thermal expansion (Θ_t in N m^{-2} K^{-1})	-11×10^{-6}
Initial strain of SMA (ε_i)	0.03090
Heat convection coefficient (h_0 in J m^{-2} s^{-1} K^{-1})	28.552
Heat convection coefficient (h_2 in J m^{-2} s^{-1} K^{-1})	4.060×10^{-4}
Diameter of wire (in m)	3.5×10^{-6}
Length of wire (in m)	0.065
Ambient temperature (T_θ in °C)	27
Martensite to austenite transformation temperature (T_{fa} in °C)	70
Austenite to martensite transformation temperature (T_{fm} in °C)	55
Spread of temperature around (T_{fa} in °C)	6
Spread of temperature around (T_{fm} in °C)	4.5

A. Fabrication of PDMS coating

Since PDMS is in liquid form, the ideal technique for coating is dip-coating technique which is low cost, simple processing and high coating quality compare to other technique such spraying, spin coating and meniscus coating. Before going further on the technique, the preparation for PDMS solution was carried out. Encapso K is the type of material used for the coating which is a water clear encapsulation rubber. It is non-hazardous and cure without generating any dangerous fume or heat that

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makes it suitable for clean environment. The material is divided into two parts which are part A and part B, the hardener. These two liquids are mixed together by mix ratio 1A:1B of weight and stir for at least 5 minutes. The mixed liquids cured after 24 hours at room temperature. During the preparation of the liquid, vinyl glove and long sleeves were used to minimize contamination risk.

Dip coating is withdrawal of excess liquid from the coating medium. The formation process takes a few stages which were immersion, withdrawal, consolidation drying and curing as in Fig. 1. At first, the immersion was when the SMA wire was immersed in mixed liquid of Encapso K. Then, followed by withdrawal of the SMA wire from the mixed liquid to remove excess mixed. Thirdly, the consolidation means that the process involved draining, evaporation and hydrolysis. The last stage of the process involved the curing of the mixed liquid that coat to the SMA at room temperature which is 27^{o}C.

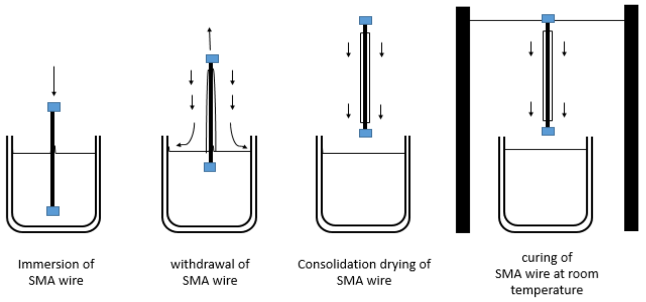


Fig. 1: Process of dip-coating technique

B. SMA Actuated Flapping Plate

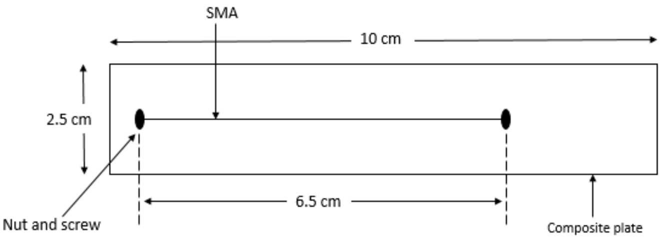


Fig. 2: SMA configuration on composite plate (top view)

The SMA wire is attached to a piece of composite plate as shown in Fig. 2. Composite plate is ideal to be used since it is anisotropic and the properties can be altered for specific applications. In aerospace industry, composite material is one of the main material used as it has high strength and stiffness at low weight[19]. Since this conceptual design is used for flapping wing, composite is a suitable material because it is flexible, light and most importantly able to withstand to external load when SMA pull force is applied on it. SMA wire is ideally use as an actuator due to one of the properties which is high power to weight ratio. This gives it high strength in direct-drive applications that will eliminate the use of power transmission. The change on shape due to two type of phase during heating and cooling which are heating process is transformation of martensite to austenite phase while the cooling process is the transformation of austenite to martensite phase. When there is flow of electric current, the temperature of the SMA wire start to increase due to Joule effect. This is where the heating process takes place and the SMA wire start to contract. A pull force is created by the contract of SMA wire and deflect the composite plate until it reach the maximum short length. The intensity of the electrical power that passes through the SMA wire can extend the flap movement. When the actuation of the SMA wire is stop, the SMA wire is cooled by natural convection then return to the original shape and the composite plate also return to original position. The cooling process is either by controlling the current by LabVIEW, when the strain produce from deflection is larger than the desired strain or directly cutting off the current from power supply. The SMA wire will be cooled by the surrounding air. However, SMA wire is not well known as an actuator because of its behavior and properties which is nonlinear.

C. Temperature Feedback

SMA is a thermomechanical materials, where it is changing in shape when heated and cooled. If it is cooled under the critical temperature of means that it has enter the martensite phase. During this phase, the properties of SMA easily being manipulated by wide range of strain but not much changes in stress. While, in austenite phase which is cooling process, the SMA return back to its original shape. Fig. 3 shows the block diagram for the temperature feedback control system. The controller represent the LabVIEW software which will control the SMA wire by gain the reading of the current temperature from thermocouple sensor.

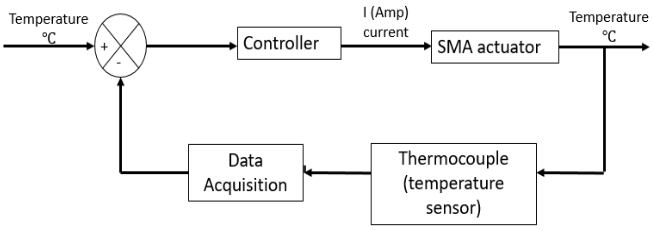


Fig. 3: Block diagram of a temperature feedback control system for the SMA actuator

V. RESULTS AND DISCUSSIONS

Before conducting the experiment, preliminary test on the relationship between current required to actuate the SMA wire and composite plate was conducted. Based on the conducted experiment, the results presented as follows. Firstly, the comparison data of SMA coated with PDMS and SMA without PDMS against time as in Fig. 4. The experiment was conducted under 25.77^{o}C room temperature. The current was set to 0.62 Amp and the SMA wire will slowly contract and thus deflect the composite plate for 60s in the heating process after which the current was decrease to 0 Amp. This is where the cooling process takes place for 30s to get to the initial length or to reach the surrounding temperature. From the graph, it is shown that SMA wire without coating with PDMS indeed achieve high temperature which is 55^{o}C while the SMA wire coated with PDMS only achieve temperature at 45^{o}C. However, the rate of cooling for SMA wire without coated with PDMS and SMA wire coated with PDMS give 1.805^{o}C s^{-1}

and 1.173°C s^{-1} respectively. This could happen due to the PDMS has retained the temperature of SMA wire and takes more time to cool.

For the second experiment conducted, the current was increased from 0 Amp to 0.7 Amp. Based on graphs shown in Fig. 5, SMA wire without PDMS coating in (a) consume more power which is 1.2 watt while the in (b) which is SMA wire coated with PDMS only use 1.08 watt in order to deflect the composite plate. This make the difference in percentage is 11.11%, while the difference in deflection of the composite plate between (a) and (b) is 9.3%. This result shows that, PDMS can help in reduce the power consumption.

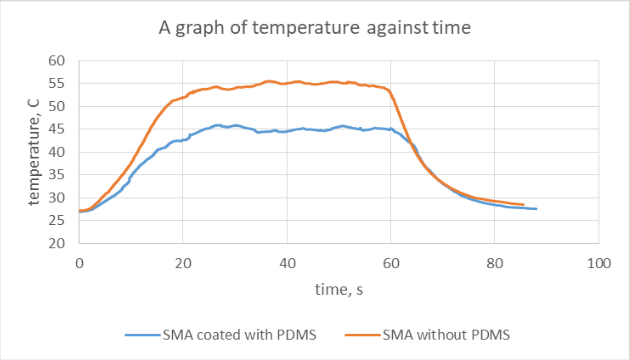
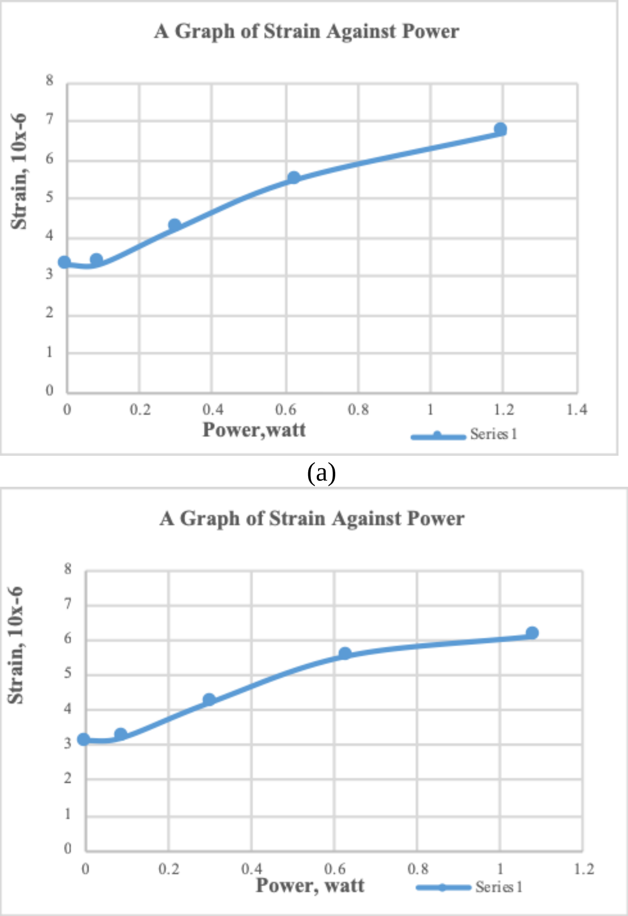


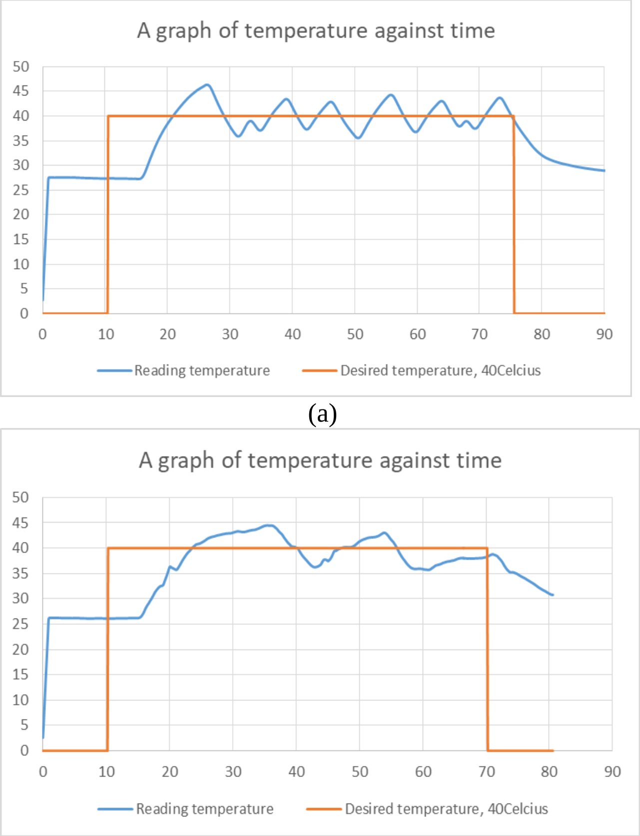
Fig. 4: Temperature change of SMA wire with and without coating with constant current supply



(a)

(b)

Fig. 5: Graph of strain against power for two type of SMA wire conditions. (a) SMA wire without PDMS coating. (b) SMA wire with PDMS coating.



(a)

(b)

Fig. 6: Comparison between temperature reading from thermocouple and desired temperature against time. (a) SMA wire without PDMS coating. (b) SMA wire with PDMS coating.

Comparison between graph in (a) and (b) shows the overshoot and time response to achieve steady state as in Fig. 6. The current flow was controlled using PID implemented using LabVIEW. The desired temperature is 40°C that is represented by the orange line that input from controller then compare with temperature reading by using thermocouple represented by the blue line. When using SMA wire coated with PDMS as the actuator for composite plate, the overshoot is 44°C, lower than value of SMA wire without PDMS which is 46°C, this gives difference in 4.35%. In (b) also shows that the time response to achieve steady state faster compare in (a) which takes longer duration to reach steady state.

VI. CONCLUSION

The aim of this project was to identify the best actuator concept to be implemented in the design of the wing, as the SMA wire and spring will be used instead of motor. SMA is able to contract upon electrical heating and has been used as artificial biceps that allows the wing to contract. The response of SMA is relatively fast using Joule heating, however cooling through natural convection is slow. The result show that PDMS coating increased efficiency of the SMA actuation by improving the time response and the reducing the overshoot of the response SMA actuator. By coating the SMA with PDMS, the development of a viable means to increase the cooling rate of SMA wire would prove advantageous with respect to the attainable stroke length and range of the motion at increasing speed. In addition that, the PDMS coating reduces to power consumption during actuation as it reduces heat loss. The findings are critical in the development of a high actuation frequency flapping wing model.

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