DESIGN, FABRICATION, EVALUATION OF LOW-SPEED UAV WING FLAP ACTUATED WITH SHAPE MEMORY ALLOY

SEOW AIK KHIAM

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

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SEOW AIK KHIAM

School of Mechanical and Aerospace Engineering

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Abstract

The novel properties of shape memory alloys (SMA) are very attractive for providing new solutions to challenging problems in aerospace engineering. Although SMA possess very high kinetic output and instantaneous actuation upon heating, owing to their slow cooling rate, difficulties have been encountered in using them as actuation mechanisms for some aerospace applications requiring repeated actuations under relatively high frequency. The project is a feasibility study to control a wing flap using SMA. Attention has been paid to conceptual design of actuation mechanisms, controllability of the actuation, and the response rate of SMA actuation. It is known that the cooling rate of SMA depends on several parameters including the materials characteristics, the geometric factor and the environmental condition. By optimizing the first two factors and taking into account the third and fourth parameters, it is possible to optimize the cooling speed of SMA thus increasing the actuation frequency within a certain range allowed by the design. The project will progress through four phases; the first phase is to understand the principles behind the shape memory effect, and this is done through extensive heat treatments, thermo-mechanical trainings and measurement. It is then followed by design, fabrication and actuation tests for two concepts, namely the shim-based version and hinge-based version. Flexible skins, a key requirement to smooth camber change, are also explored and experimented. A mechanism that will engage and disengage the SMA wires during operation is also studied. Finally, the controllability of actuation is studied.
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Chapter 1: Introduction

1.1 Morphing Aircraft

Most modern aircrafts employ shape change to suit different flight conditions. For example, the control surfaces of aircraft have been extensively used for providing stability and control, and this is achieved through changing the shape, e.g. increased camber. Furthermore, in order to reduce drag, almost all aircrafts are fitted with retractable landing gear systems. Even the first successful controlled and powered flight by the Wright brothers involved differential twisting of the wings for generating the control forces [1].

Many aircraft designers are awed and inspired by nature’s master aviators; the birds. Birds are efficient flying ‘vehicles’; capable of reshaping their wings and tails to soar, dive and maneuver with ease. An aircraft that is able to fly like a bird will have many advantages, including fuel efficiency and better aerodynamic performance. A morphing aircraft can then be defined as an aircraft that changes configuration (like the bird) to maximize its performance at radically different flight conditions [1].

The most important part of an aircraft is the wing since it creates most of the required lift, and their cross sectional shape and size determines the suitability of the aircraft to a particular mission [1]. Therefore, a lot of efforts have been placed on morphing the wing; some examples are telescopic wing, swept wing, DARPA/ AFRL/ NASA Smart Wing that is capable of wing twist, etc.
Chapter 1: Introduction

The use of conventional methods of actuation, such as hydraulics, pneumatic or servo-actuators, is usually heavy and complex. Therefore, enabling wing morphing with these conventional actuators will often result in a heavy weight penalty! Very often, a tedious maintenance schedule is accompanied for these actuators.

Smart materials and structures or intelligent material systems have received increasing attention because of their scientific and technological significance [2]. Shape memory alloy (SMA) is one such material because of its unusual properties such as shape memory effect and superelasticity, and the high force-to-weight ratio will provide SMA an edge over conventional actuators in terms of weight saving.

There are many other types of smart actuation, and some examples are Shape Memory Polymer, Dynamic Modulus Foam and compliant mechanism. However, Shape Memory Polymer is more suited as a morphing skin design whereby Dynamic Modulus Foam (Dynamic Modulus Foam is a low density, adaptive structural composite foam system [3].) which is used as a wing chord-varying core only allowed single activation. Designing compliant mechanisms for actuation require relatively complex analyzing and piezoelectric actuators, though capable of producing high frequency actuation, often involves very small displacements.

1.1.1 Hinge-less Control Surfaces

Conventional control surfaces are usually separate flaps that are attached to the wingtips through a hinge; these give rise to discontinuous boundaries resulting in early airflow separation. This will lead to reduce lift and increased drag. The use of a smooth
continuous control surfaces [4], on the other hand, delays the onset of flow separation and also improves the lift and stall angle characteristics.

Actuation of a control surface is usually done by means of hydraulic or servo actuator. An additional linkage to link the actuator to the control surface may be required; sometimes the linkage will protrude beyond the airfoil shape. The radar cross section of the aircraft may also be affected by such discontinuity and protrusion, which is undesirable with respect to military operation. The radar cross section of an object exposed to radar is a fictitious area that describes the intensity of the wave reflected back to the radar [5].

One important requirement of achieving a smooth continuous control surface is flexible skins that can stretch and return (to original size) during actuation. These flexible skins will be able to undergo large strains, have low in-plane stiffness and very high out-of-plane flexure bending stiffness.

1.1.2 Aerodynamic performance of hinge-less aileron

The most thorough documentation of the aerodynamic performance of a hinge-less aileron would be the DARPA/ AFRL/ NASA Smart Wing program whereby a 16% scale semi-span wind tunnel model was tested [6]. The trailing edge control surfaces were actuated using embedded SMA wires with span wise twist via a SMA torque tube. Results from the tests conducted showed that improvement were possible through the use of smoothed contoured trailing edge surfaces and wing twist. A table obtained from [6] was shown below.
Chapter 1: Introduction

Table 1-1: Aerodynamic improvement achievable with hinge-less control surfaces in percentage [6]

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Deflection of Wing Twist (Deg.)</th>
<th>Lift ΔCL</th>
<th>Roll ΔC(l)</th>
<th>% Improvements Lift</th>
<th>% Improvements Roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flap Only (Test 1)</td>
<td>7.5</td>
<td>0.0581</td>
<td>0.0193</td>
<td>9.7%</td>
<td>10.2%</td>
</tr>
<tr>
<td>Flap and Aileron Combined (Test 1)</td>
<td>7.5</td>
<td>0.0916</td>
<td>0.0387</td>
<td>17.6%</td>
<td>17.1%</td>
</tr>
<tr>
<td>Aileron Only (Test 1)</td>
<td>5</td>
<td>0.015</td>
<td></td>
<td>8.0%</td>
<td></td>
</tr>
<tr>
<td>Aileron Only (Test 2)</td>
<td>10</td>
<td></td>
<td>0.0189</td>
<td></td>
<td>10.5%</td>
</tr>
<tr>
<td>Wing Twist (Test 2)</td>
<td>3</td>
<td>0.0344</td>
<td>0.0193</td>
<td>8.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.0502</td>
<td>0.0296</td>
<td>11.5%</td>
<td>15.6%</td>
</tr>
<tr>
<td>Wing Twist (Test 1)</td>
<td>1.4</td>
<td>0.0406</td>
<td>0.0218</td>
<td>10.0%</td>
<td>12.8%</td>
</tr>
<tr>
<td>Combined Aileron &amp; Wing Twist (Test 2)</td>
<td>+10° Aileron</td>
<td>0.0567</td>
<td>0.031</td>
<td>15.3%</td>
<td>17.3%</td>
</tr>
<tr>
<td></td>
<td>+4.5° Wing Twist</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One of the most critical results and achievements of the Smart Wing Phase 1 program was the improvement in lift and roll, achieved from a flap actuated by SMA and aileron as compared to a conventional hinged configuration. An improvement of 8 – 10.5% over an aileron deflection of 5 – 10° was achievable [6].

The following graph showed the improved aileron effectiveness over a hinged configuration.
Chapter 1: Introduction

![Aileron Effectiveness Diagram]

Figure 1-1: Aileron effectiveness at Mach 0.25 and dynamic pressure of 90psf [6]

It can be observed that separation reduction due to the contoured aileron resulted in improved lifting surface and a lower deflection angle in comparison with a conventional aileron.
Chapter 1: Introduction

1.2 Objectives and Scope

This project is a feasibility study to control a flap, making use of SMA as the actuator. The wing profile selected was NACA0012 and attention has been paid to conceptual design of actuation mechanisms, controllability of the actuation, and the response rate of SMA actuation. Flexible skins to provide smooth camber change will also be explored.

Among the various types of actuators, SMA is chosen as the actuator for the project. Comparing SMA with conventional methods of actuation, advantages of SMA are obvious; better force to weight ratio can be achieved, the actuator design can be very compact and simple, material itself is corrosion resistant and usually minimum wear and tear will be involved.

It is known that the cooling rate of SMA depends on several parameters including the materials characteristics, the geometric factor and the environmental condition. By optimizing the first two factors and taking into account the third and fourth parameters, it is possible to optimize the cooling speed of SMA thus increasing the actuation frequency within a certain range allowed by the design. Careful consideration of the actuator design will also play a vital part in improving the response of the SMA. SMA offered very good force to weight ratio when compared with conventional actuators like hydraulics or servo actuators, therefore if the response of SMA could be improved, it would definitely be beneficial.
1.2.1 **Objective of Project**

The objective of this project is to design and develop a wing flap to enable camber morphing for a low speed Unmanned Aerial Vehicle, making use of shape memory alloy (SMA) as the mode of actuation.

SMA has been reported to have poor operational bandwidth [7], which is usually caused by the slow cooling rate of the alloy itself. Therefore, ways to improve the response of SMA actuator will be studied. Lastly, flexible skin to accommodate the shape change during the actuation will be explored.

1.2.2 **Scope of Work**

The wing flap is designed based on the information provided by DSO National Laboratories as shown in Table 1-2. These criteria are based on a low speed (25m/s), 15kg class Unmanned Aerial Vehicle with a typical maneuver condition responding to load factor of 3g. Figure 1-2 shows the flow of the project, from conceptual design to the actuation tests.

**Table 1-2: Design parameters for flap**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of Attack</td>
<td>10º</td>
</tr>
<tr>
<td>Flap deflection</td>
<td>5º</td>
</tr>
<tr>
<td>Lift Coefficient, C_{Lactuate}</td>
<td>0.06</td>
</tr>
<tr>
<td>Lift Coefficient for zero flap deflection, C_{Zero}</td>
<td>0.045</td>
</tr>
<tr>
<td>Reference Area, S</td>
<td>0.6815m²</td>
</tr>
<tr>
<td>Max. Velocity, V_{max}</td>
<td>25m/s</td>
</tr>
<tr>
<td>Density of Air, ρ</td>
<td>1.23kg/m³</td>
</tr>
<tr>
<td>Safety Factor, SF</td>
<td>1.2</td>
</tr>
<tr>
<td>Rate of Actuation (for both directions)</td>
<td>5º/sec</td>
</tr>
</tbody>
</table>
The work begins with conceptual design, making use of ‘SolidWorks’, a computer-aided design software, to model all the necessary parts. Three wing actuation concepts are conceived. This is followed by the selection of the structural materials, taking into account the density, elasticity and stiffness of the material. These materials should have good...
compatibility with the SMA and are able to withstand the aerodynamic load, which will be calculated based on information provided in Table 1-2.

After the initial conceptual designs are finalized, the project will proceed through four phases; Phase 1 – Experimental works with SMA, which circles around heat treatments, thermo-mechanical training and measurement of the heating/cooling time of the various alloys, Phase 2 – Fabrication and testing of the shim-based concept, Phase 3 – Fabrication and testing of the hinge-based concept. Finally, in Phase 4 the controllability of the wing flaps is studied.

In Phase 1, extensive work on SMA heat treatment and thermo-mechanical training is carried out. Three types of SMA are used, namely SM495, NTC05 and Ni$_{25}$Ti$_{50}$Cu$_{25}$. SM495 is a nickel-titanium alloy, whereas NTC05 and Ni$_{25}$Ti$_{50}$Cu$_{25}$ are nickel-titanium alloys with copper added. All three SMAs are melt-spun and available as un-trained alloys. This is an important phase as it allows the author to obtain a better understanding of the principles behind the shape memory effect and the behaviour of different types of SMA. Attention is paid particularly to transformation hysteresis, which is a parameter that will determine how fast a SMA can recover.

In Phase 2, the shim-based wing prototype is developed. The phase begins with the fabrication, assembly and testing of a rib based on concept #2. The wing prototype is then fabricated upon successful testing of the rib. All actuation are performed using SM495 wires (this SMA is trained in-house), and the target is to achieve the flap deflection requirement of $5^\circ$ per second for both upward and downward directions. Finite element
Chapter 1: Introduction

analysis and structural load test are conducted to verify the structural integrity of the rib assembly and the strength of the metallic shim. This is done using CosmoWorks (finite element analysis software) and Instron tensile machine respectively. Flexible skin, which is an important feature for providing smooth camber change, is explored in this phase. In addition, a mechanism to disengage the SMA wire is designed and tested.

In Phase 3, the hinge-based wing prototype is developed. A commercial off-the-shelf SMA (Flexinol® - purchased from the company known as Dynalloy Inc.) is used as the actuator. This is because it possesses more stable characteristics, compared with the in-house trained SMAs. However, the actual type of heat treatment and thermo-mechanical training applied to the SMA are not known. The objective of the project is achieved in this phase with a demonstration of camber morphing.

Investigation of the controllability of the SMA actuated flap prototype through testing and monitoring is conducted in the final phase. Controllability is governed by the deflection angle of the wing flap and rate of actuation in cycles per second. The wing prototype will be termed highly controllable if large deflection is achieved using SMA with small cross-sectional area, and attaining the required actuation rate shown in Table 1-2. The targeted deflection angle is 5 degrees or larger and using SMA having diameter of 0.2mm or smaller. Finally, the targeted actuation rate is 5 degrees per second or better.
Chapter 1: Introduction

1.3 Thesis Structure

The thesis is structured according to the flow of project. Chapter 2 is a literature review on the various types of actuation used for controlling flaps and control surfaces. Actuators using shape memory alloy, piezo-actuator, shape memory polymer, and other types of novel actuations are discussed. Flexible skin will also be discussed in the last section of the chapter.

Chapter 3 covers mainly the heat treatment, thermo-mechanical training and measurement of SMA. Three types of melt-spun and un-trained SMA are used, namely SM495, NTC05 and Ni25Ti50Cu25. Heat treatment temperatures ranging from 500°C to 600°C are experimented on these alloys to understand the effect of heat treatment. The thermo-mechanical training process is discussed next. A data acquisition system, National Instruments CompactDAQ, will be set up for measuring changes in temperature, resistance and voltage as the SMA wires are being heated and cooled. The heating time and cooling time are also monitored using Instron tensile machine. These measured data will then be used to calculate the heating-cooling rates of these alloys. Differential Scanning Calorimeter is used to determine the transformation temperatures of these SMAs, namely martensite start and finish temperatures, austenite start and finish temperatures. These plots will be presented.
Chapter 1: Introduction

Chapter 4 concentrates on the shim-based wing prototype developmental work; from the conceptual designs to the wing flap actuation tests. The design and selection of the rib, the sizing of the metallic shim to sustain the aerodynamic load, SMA force calculation and the fabrication process of the wing prototype are presented. Next, the initial actuation tests using SM495 wires are described. This is followed by the design and fabrication of the flexible skin and the work on the engage-disengage mechanism. Finally, in the last section of the chapter, the problems encountered and observations made throughout the design and testing stages are discussed.

Chapter 5 focuses mainly on the transition from the shim-based wing prototype to the hinge-based wing prototype. The improvements made are set to tackle the drawbacks presented in Chapter 4, Section 4.4.5. The stiffness of the overall prototype assembly will be improved in order to allow the use of small diameter SMA. A locking mechanism is designed to lock the flap in the desired position, achieving camber morphing. Static load test and actuation test (with load) are presented. Finally, the controllability of the wing flaps is discussed.

Chapter 6 summarizes the work performed for this research project and recommendations for the future works are discussed.
Chapter 2: Literature Review

2.1 Shape Memory Alloy

Shape memory alloy (SMA) is one material that exhibits shape memory properties, in another word, has the ability to ‘remember’ a predetermined shape. When the SMA is below a certain temperature, it can be easily deformed and stretched to another shape, which it will retain. However, when the temperature is raised, the alloy will undergo phase transformation to austenite that causes it to return to its original shape.

The most common SMA is nitinol [8], a Nickel-Titanium alloy that was discovered accidentally by a team at the U.S. Naval Ordnance Laboratory, while searching for non-corrosive marine alloys in the 1960s. However, the history of shape memory alloy dated back to 1932 when Swedish researcher Arne Ölander observed the shape recovery abilities of gold-cadmium alloy and noted its potential for creating motion.

The basis of the shape memory effect [9] is that the materials can easily transform to and from martensite. Martensitic transformations are generally displacive type of transformation that does not require long-range movements, and they are form upon cooling from the austenite phase. Crystallographically, the transformation from austenite to martensite occurs in two parts, Bain strain and lattice-invariant shear. Bain strain consists of all the atomic movements needed to produce martensite from austenite while lattice-invariant shear is an accommodation step. For shape memory to occur to any significant extent, the accommodation mechanism must be reversible, thus twinning is the dominant accommodation process.
Twin boundary is a mirror plane; atoms situated on that boundary see the same number and types of bond in both directions. Twin boundaries are usually of very low energy interfaces and they are mobile. Therefore it is easy to move these boundaries through application of a stress to convert from one orientation to another.

The shape memory process can be shown schematically (Figure 2-1).

![Figure 2-1: Shape memory process](image)

Four temperatures during transformation are, martensite start and finish temperatures ($M_s$ and $M_f$ respectively), austenite start and finish temperatures ($A_s$ and $A_f$ respectively). There will be no shape change at temperature below $M_f$ and it will remain deformed when a stress is applied until it is heated. Shape recovery begins at $A_s$ which is the onset of...
austenite formation. Austenite is completely formed at $A_f$. Figure 2-2 shows the four transformation temperatures plotted against change in length of a SMA specimen.

![Figure 2-2: Wire length versus temperature](image)

As can be observed from the above plot (Figure 2-2), there is a difference between the heating and cooling transformation. This is termed hysteresis and it differs for different types of alloys. Typical ranges are $20^\circ$ to $40^\circ$. Adding ternary elements that are chemically similar to Ni or Ti can alter the transformation hysteresis. For example, substituting of Cu for Ni could remarkably reduce the transformation hysteresis and drastic reduction from 26 $^\circ$C to 6 $^\circ$C with 25% Cu addition is achievable.

The yield strength of SMA changes significantly during transformation. In the martensite stage, the yield strength is extremely low compared to austenite since they are easily deformed by moving twin boundaries. Austenite, on the other hand must be deformed by dislocation generation and movement, thus resulting in much higher yield strength. A typical plot of load vs. time is shown in Figure 2-3.
Chapter 2: Literature Review

2.1.1 Types of shape memory effects

![Diagram showing types of shape memory effects]

Figure 2-4: One-way shape memory effect
Figure 2-4 shows the one-way shape memory effect, as the name implies, it is a one time only deployment. At below $M_f$, the martensite are deformed, as it is being heated to above $A_f$, the original contracted shape will be recovered. However, the contracted shape remains when the specimen is cooled again to below $M_f$.

Figure 2-5 shows the two-way shape memory effect, the specimen will extend when heated to above $A_f$ and contracts when cooled to below $M_f$. The extension/contraction will repeat as the specimen is being heated/cooled. Two-way shape memory effect is achieved through special thermo-mechanical treatment (training) to produce micro-stresses in the parent phase, which in turn program the specimen to behave as a stress-induced martensitic transformation.

Shape memory alloys also exhibit superelasticity [10], a property to return to original shape upon unloading after a substantial deformation. This type of shape memory effect is temperature independent. Martensite can form above $M_s$ if stress is applied; this is called stress-induced martensite. The stress required to produce stress-induced martensite
Chapter 2: Literature Review

increases with increasing temperature. The temperature range to produce stress-induced martensite is from $M_s$ to $M_d$, above which the critical stress for inducing martensite is greater than that needed to move dislocations. Since the applied stress is basically uniaxial, only one orientation of martensite is selectively formed, and this imparts an overall deformation to the specimen. The original shape is restored when the stress is removed.

2.1.2 Application of shape memory alloy

Application of shape memory alloys [11] can be classified into four categories; namely free recovery, constrained recovery, work production (actuators) and superelasticity.

1. Free recovery

This category includes applications whereby the sole function is to cause motion or strain. Example of such application commercially is the Ni-Ti spectacle frame. The martensitic Ni-Ti makes the frame soft and comfortable to wear. But if accidentally deformed, the frame can recover its original shape by immersing in hot water.

2. Constrained recovery

This is the most widely exploited use of shape memory alloys; the memory element is prevented from changing shape thereby generating a stress. Examples of application are couplings for joining aircraft hydraulic tubing, couplings for marine and industrial environments, fasteners used to fasten braided shielding to the back of a connector, and electrical connectors.
3. Work production (Actuator)

This is the type of application where the shape memory material recovers against a stress, thus producing work (Figure 2-6).

![Figure 2-6: Simple SMA spring actuator](image)

These actuators can be further classified into thermal actuators and electrical actuators and heat engines. Thermal actuators are designed to respond to a change in temperature and are generally competing with bimetal, while electrical actuators are generally used to do work replacing servo-motors, solenoids, hydraulics, pneumatic devices, etc. Some examples of these actuators are VEASE® actuator (capable of lifting 0.5kg a distance of 2cm over 10,000 times), SMArt Clamp to control flow of fluid in an intravenous feeding tube, Ni-Ti springs to control the shifting in automatic automobile transmission, Ni-Ti spring in a coffee maker to control brewing temperature, and circuit breakers. Heat engines, on the other hand convert thermal energy to mechanical energy. There were many ingenious designs but it appeared clear that these heat engines efficiencies were very low.

The SMA actuators to actuate the wing flap falls under this category of application whereby electrical heating will be used to heat the wire.

Superelasticity is an isothermal event, thus applications based on it must be in a well-controlled temperature environment. Most of the successful applications of superelastic Ni-Ti wires were related to the human body in one way or another. Some examples are orthodontics, Mammalok® needle wire localizer used to locate and mark breast tumors, guidewire – used as a guide for catheters passing through blood vessels, and suture anchor.

2.1.3 The advantages and disadvantages of SMA

The advantages of SMA are as follow; simple and compact – no complex piping involved when compared to hydraulic or pneumatic systems. Next is minimum wear since no moving parts are involved with respect to the actuator itself. This implies residues or particles caused by wear and tear are not present. Therefore, a cleaner working environment can be produced. No moving parts (compared with mechanical, e.g. gears) also would imply lower vibration therefore less noise would be produced. Next is high power to weight ratio, and lastly, corrosion resistant and biocompatibility therefore making SMA a suitable candidate for medical usage.

The disadvantages are; low energy efficiency, limited bandwidth due to heating and cooling restrictions. SMA will lose its shape memory effect if it is overheated, while cooling is limited to the cooling capacity of the SMA itself. Degradation and fatigue – as the strain and stress is increased, the cycles of operation would reduce. Lastly, the transformation of SMA is very much dependent on the heat treatment and thermal cycling.
Chapter 2: Literature Review

2.2 Types of Actuation

The most traditional method of actuation is hydraulics. Hydraulic technology first gained a foothold in aircraft flight control after World War II, when fluid power was introduced for some secondary system’s control [12]. In modern aircraft, hydraulic is used for flight controls, flap/ slat drives, landing gear, nose wheel steering, thrust reversers, spoilers, rudders, cargo doors and emergency hydraulic-driven electrical generators.

Mechanical drives is another type of actuation system which makes use of an electric motor to drive a series of drive shafts, gearboxes and mechanical linkages, to produce the required extension and retraction of the flap [13]. They were popularly applied in remote control planes or possibly smaller UAV where speed is lower. These servo actuators were usually used to control the ailerons, rudders & elevators & even fuel injection for RC planes through a series of linkages. One such actuator is shown in Figure 2-7.

Figure 2-7: A Futaba S-148 Servo & a disassembled servo [14]
Other types of actuation systems include cable drives and pneumatic system. Figure 2-8 shows a telescopic wing, developed by Julie Blondeau and Darryll J. Pines [15]; pneumatic cylinders were used to extend the span of the wing.

![Figure 2-8: Pneumatic telescopic spar [15]](image)

In the following sections, shape memory actuators, other types of smart actuation and flexible skins will be described.

### 2.2.1 Shape Memory Alloy Actuator

The novel properties of shape memory alloys (SMA) are very attractive for providing new solutions to challenging problems in aerospace engineering. Most applications that utilize the shape memory effect of SMA to deploy structures/components require only one-way memory effect. Although SMA possess very high kinetic output and instantaneous actuation upon heating, owing to their slow cooling rate, difficulties have been encountered in using them as actuation mechanisms for some aerospace applications requiring repeated actuations under relatively high frequency. Researchers were
disappointed by the low bandwidth when they attempted to apply SMA as actuator for an aircraft.

DARPA/ AFRL/ NASA conducted an extensive ‘Smart Wing’ program in two phases. Under phase 1, SMA based hinge-less, smoothly contoured trailing edge control surfaces, and actively variable wing twist using SMA torque tubes were investigated. Results from their wind tunnel tests were briefly described in Chapter 1, Section 1.1.2. However, they too realized that SMA was unable to meet the high actuation rate requirement for Unmanned Combat Aerial Vehicle (typically in the range of 60 to 75 degrees per second with maximum deflection of about 20 degrees) [7, 16], possibly due to the slow cooling rate of SMA.

Belt-rib concept [17], a flexible wing rib developed by German Aerospace Center (DLR) to pursue the target of a ‘structronic’ solution for airfoils with selectable camber was shown in Figure 2-9. ‘Structronic’ was used by DLR to describe the conflicting requirement of a flexible structure for shape control and at the same time able to provide some degree of stiffness. SMA was suggested as an actuator element to provide tension forces, arranged in a truss configuration. Another option suggested was to embed active material (SMA or piezoelectric materials) to directly induce the desired camber variation in the belt-rib.
A patented airfoil camber control apparatus is shown below. This apparatus utilizes a cable of shape memory alloy affixed at its ends to a front interior portion of the airfoil. A tensioning system is connected to a rear interior portion of the airfoil and to the cable. When electrical current is applied to the cable to heat it, it returns to its remembered, shorter length, thereby applying tension to the tensioning system to alter the position of the rear portion of the airfoil relative to the front portion [18]. This is shown in Figure 2-10.

Figure 2-10: Variable camber control of airfoil [18]
This is another patent with a shape memory alloy actuation system in one of the embodiments. A control surface for an aircraft has a reinforced elastomer surface on a surface of the aircraft and has a perimeter attached to the aircraft. An actuation mechanism moves the reinforced elastomer surface from a first position, substantially conforming to a mold-line of the aircraft, to a second position, protruding from the mold-line of the aircraft [19]. Figure 2-11 shows the concept.

![Figure 2-11: Control surface for an aircraft [19]](image)

In this next patent, a pliant, controllable contour control surface comprising a first flexible face-sheet (elastomeric thermoplastic material) formed to a first initial contour of a control surface, and a second flexible face-sheet formed to a second initial contour of the control surface. The first and second face-sheets each have a set of pre-strained shape memory alloy tendons embedded therein, extending from a leading edge to a trailing edge of the control surface. Each set of the shape memory alloy tendons is separately connected to a controlled source of electrical current such that tendons of the first and second flexible face-sheets can be selectively heated in an antagonistic, slack-free relationship, to bring about a desired modification of the configuration of the control surface [20]. The concept is shown in Figure 2-12.
Chapter 2: Literature Review

Figure 2-12: Adaptive control surface using antagonistic shape memory tendons [20]

Next is an articulated control surface for flight control. It utilizes a moldable control surface that is shaped by contracting and elongating shape memory alloys embedded within the control surface. The shape memory alloys contract when heated via an applied electric current and elongate when cooled (the electric current is removed). The resulting control surface is capable of generating a curved surface without any electro/mechanical or hydraulic control systems [21].

Figure 2-13: Articulated control surfaces [21]
Shape memory alloy is also applied as an actuator in many other areas such as control surface for a marine craft or camber morphing of a windmill blade. Following are two such patents that make use of SMA.

An articulated control surface is provided for hydrodynamic control utilizing a moldable control surface. The central surface is shaped by contracting and elongating wire bundles fabricated with shape memory alloys, and these bundles are located in an adjacent cooling chamber. The shape memory alloys contract when heated via an applied electric current and elongate when cooled (the electric current is removed). A pair of wire bundles is anchored inside the cooling chamber. Each bundle is routed over several pulleys in such a manner that a lateral movement is produced at the actuator end of the wire. A pair of bundles acts in opposition to maintain dynamic tension at the actuator end. Cooling flow to opposing wire bundles is controlled independently to enhance response time and reduce power requirements. The actuator is a post extending from the cooling chamber to the trailing edge structure of the control surface [22].

Figure 2-14: Articulated fin/wing control system [22]
Chapter 2: Literature Review

The following invention relates to a windmill power generation system which includes at least two variable camber blades fastened to a rotating hub. The blades are driven by a fluid such as wind. Each of the variable camber blades has embedded shape memory alloy members. The system also includes a source of electrical power connected to the shape memory alloy members for varying the shape of the blades in response to changes in the speed of the fluid driving the blades. The power generating system further includes a power regulator connected to the electrical power source for regulating the electrical power being supplied to the shape memory alloy members and a controller for transmitting a power command signal to the power regulator [23].

2.2.2 Other Types of Smart Actuation

1. Piezoelectric actuators

Piezoelectric actuators are solid-state ceramic actuators which convert electrical energy directly into linear motion (mechanical energy). There are many applications where piezoelectric actuator may be used; some examples are life science, medicine, biology, data storage, semiconductors and microelectronics, precision mechanics and mechanical engineering such as vibration cancellation, smart structures, and micro-pumps [24]. Many
applications and studies of piezoelectric actuators had been concentrated in the vibration control area for aerospace. Some examples were; buffet suppression on a full-scale F/A-18, flutter damping, turbine engine vibration control, active acoustic control of aircraft, and Smart Spring for vibration suppression of rotorcraft blades [25]. In another experiment conducted, piezoelectric actuators and sensors were utilized to control the aeroelastic response of a 0.6m span wing [26].

A small expandable morphing wing (Figure 2-16), actuated by DC motor, reduction gear, and fibre reinforced composite linkages was designed at Konkuk University of South Korea. Piezo-composite actuators were attached under the inner wing section to modify the camber of the wing, which was reported to be effective producing additional lift of 16% [27].

![Wing in folded state](image1) ![Wing in fully expanded state](image2)

Figure 2-16: Expandable morphing wing and piezo-composite actuator [27]

Perhaps the application more closely related to flap actuation utilizing piezoelectric actuators was none other than the DARPA/AFRL/NASA Smart Wing Program whereby an ultrasonic piezoelectric motor was utilized to deflect the control surface [7]. The motor was used to transmit torque efficiently through an eccentricator (Figure 2-17) to obtain high rate actuation.
Ultrasonic piezo-motor is one in which electrical energy is converted by the inverse piezo-effect to obtain oscillation of the piezo actuator at one of its resonant frequencies in the ultrasonic range, and this oscillation used in conjunction with a smooth frictional contact to obtain unlimited motion of the moving part. The increase in oscillation amplitude of the actuator due to resonance means that a lower drive voltage can be used. The working frequencies of ultrasonic motors range from 20 kHz to 10 MHz. The amplitude of the actuator motion is in the range of 20 to 200nm [28]. Piezoelectric actuators operations are usually in the high bandwidth range; microseconds-range response [29]. They have very good resolution (sub-nanometer), large force generation (up to 50kN), and electrically driven (thus allowing direct integration with operating electronics). The drawback of such actuators lies with the high voltage requirements, typically from 1 to 2 kV (as the size of the actuators increases, so does the required voltage), making them favorable only for small scale devices. Being ceramic, they are brittle requiring special packaging and protection. Piezoelectric actuators usually provide small displacement; strain in the range of 0.1-0.2%.
2. Shape memory polymer

Shape memory polymer (SMP), by Cornerstone Research Group, Inc. (CRG) [3], exhibits characteristics of both elastomer and plastic, depending on the temperature. While rigid, SMP demonstrates the strength-to-weight ratio of a rigid polymer and while heated and pliable, SMP has the flexibility of a high-quality dynamic elastomer, tolerating up to 200% elongation. SMP can be reshaped or returned quickly to its memorized shape and subsequently cooled into a rigid plastic. Unlike SMA, SMP exhibits a radical change from a normal rigid polymer to a very flexible elastic and back on command, a change that can be repeated without degradation of the material.

CRG proposed to develop a wing with an adjustable wing chord utilizing styrene based SMP as the skin, which was proven feasible (Figure 2-18). However, their phase 1 attempt to use DMF (Dynamic modulus foam) as the internal structure of the wing was not achieved. Their objective was to achieve a two-way wing chord adjustment, which was not achievable by DMF. (DMF is a low density, adaptive structural composite foam system using SMP resin that can be thermally softened and subsequently hardened.)

Figure 2-18: CRG’s initial wing concept [3]
Chapter 2: Literature Review

SMPs have at least one transition temperature ($T_g$), at which point the SMP transitions between a hard rigid plastic to a soft, pliable, elastomeric polymer. The SMP must be cooled below its $T_g$ while maintaining the desired deformed shape to “lock” in the deformation. Once the deformation is locked in, the polymer network cannot return to its “memorized”, or original shape due to thermal barriers. The SMP will hold its deformed shape indefinitely until it is heated again above its $T_g$ [30].

There are three types of thermally activated SMP; namely partially cured resins, thermoplastics and fully cured thermoset systems. There are limitations and drawbacks to the first two types; partially cured resins continue to cure during operation and changes in properties occur with every cycle. Thermoplastic SMP, on the other hand, ‘creeps’ which means it gradually ‘forgets’ its memory shape over time [30].

3. Compliant Mechanisms

A mechanical mechanism is a device used to transfer or transform motion, force, or energy [31]. A compliant mechanism also transfers or transforms motion, force, or energy. Unlike rigid-link mechanisms, compliant mechanisms gain at least some of their mobility from the deflection of flexible members rather than from movable joints only.

One such application is described [32]; compliant mechanisms were used to produce static shape changes at the leading and trailing edges of an airfoil using specially synthesized compliant mechanisms, powered by only a single actuator at each edge as shown in Figure 2-19. The compliant mechanisms produced the desired shape changes in the airfoil by transforming the input torque (or rotation) into controlled displacements of a finite number of discrete points on the airfoil contour.
Figure 2-19: Schematic of shape control using compliant mechanism [32]

Potentially, compliant mechanism has the advantage of achieving a dramatic reduction in the total number of parts required to accomplish a specified task. This will lead to a smaller number of movable joints, such as pin (turning) and sliding joints, resulting in reduced wear and backlashes, and need for lubrication. Lastly, there is a significant reduction in weight by using a compliant mechanism over their rigid-body counterparts.

However, compliant mechanisms are relatively difficult to analyze and design. Fatigue analysis is typically a more vital issue for compliant mechanisms than for their rigid-body counterparts, and the motion from the deflection of compliant links is also limited by the strength of the deflecting members.

2.2.3 Flexible Skins

Morphing aircraft wings require flexible skins that can undergo large strains, have low in-plane stiffness and very high out-of-plane flexural stiffness [33]. Though this research project is not exactly a morphing project, but the application of SMA as an actuator will definitely lay the foundation for future applications.
Gabriel et al proposed a Flexible Matrix Composite (FMC) skin for one-dimensional morphing application such as wing span, chord morphing or camber change. Analysis, experiments and parametric studies were performed. FMC comprises of stiff fibres (e.g. fibre glass) embedded in a soft high strain capable matrix material (e.g. silicone) with the idea of aligning the matrix-dominated direction along the morphing direction. The fibre-dominated direction is aligned normal to the morphing direction to increase the capacity of the FMC skin to carry out-of-plane pressure loads, and not deform excessively under such loads. The schematic are shown in Figure 2-20.

![Figure 2-20: Schematic of FMC fibre orientation for span change, and chamber or chord change [33]](image)

In another study at the same University, sandwiched skins with flexible face-sheets and cellular cores were proposed [34]. The cellular cores (honeycombed cores) can be designed to be high-strain capable, have low axial stiffness and high bending stiffness. For one-dimensional morphing application, restraining the Poisson’s contraction (or bulging) that a conventional cellular honeycomb core would otherwise experience in the non-morphing direction, results in a substantial increase in the axial stiffness in the morphing direction. This led to the development of zero Poisson’s ratio hybrid and accordion cellular honeycombs, through the combination of regular cells (positive cell angle) and auxetic cells (negative cell angle). Figure 2-21 showed the schematic the various types of cellular honeycombs under deformation.
Figure 2-21: Various types of cellular honeycombs under deformation [34]

The Smart Wing program (Phase One) by DARPA could have applied similar type of sandwiched skins as shown in Figure 2-22. Phenolic core with silicone face-sheets were shown.

Figure 2-22: Details of smart trailing edge design [35]
Flap de-lamination occurred during the second wind tunnel test [16]. The failed surface showed that the SMA flap had an unusual curve that caused the de-laminating of the face-sheet from the honeycomb core. The precise cause of the failure was not known at test time and thus this showed the uncertainty and difficulty of bonding silicone face sheets to aluminium honeycomb core.

Another two major US projects that utilized flexible skins are Morphing Aircraft Structures (MAS) program (another DARPA led effort) [36] and DARPA/AFRL/NextGen Morphing Aircraft Structures (N-MAS) program [37].

Two skin materials were investigated for MAS program; re-enforced silicone elastomeric (wind tunnel model, as shown in Figure 2-23) and shape memory polymers (envisioned for flight vehicle). It was mentioned that in order to maintain the shape, the flexible skins required a vacuum system when exposed to aerodynamic loads. After a vacuum failure during the wind tunnel test, the model encountered a flutter condition immediately following significant flexible skin dynamics.

Figure 2-23: Flexible seamless skins [36]
Chapter 2: Literature Review

A propriety flexible skin was used for N-MAS program, therefore no information was provided. The wing tunnel model showing the wing portion is shown in Figure 2-24.

![Figure 2-24: Front and top views of N-MAS wing [37]](image)

2.3 Chapter Summary

This chapter presents the literature reviews on shape memory alloys and various types of flaps/ control surfaces actuation. Firstly, conventional actuation (hydraulics, mechanical drives, cable drives and pneumatics) is briefly described. The subsequent sections provide an overview of the various types of smart actuation; e.g. shape memory actuators, piezoelectric. The flexible skins, currently studied and experimented, are presented next.
Chapter 3: Heat Treatment, Thermo-mechanical Training and Measurement of SMA

3.1 Types of SMA Considered

This is an important phase as it will allow the author to obtain a better understanding of the principles behind the shape memory effect and the behaviour of different types of SMA. Attention will be paid particularly to hysteresis, which is a parameter that will determine how fast a SMA can recover.

Three types of SMA will be experimented, taking into account the dimension, transformation temperatures and hysteresis. Table 3-1 shows the SMA selected for the project, and their transformation characteristics were determined using Differential Scanning Calorimeter (DSC).
Table 3-1: Types of SMA considered

<table>
<thead>
<tr>
<th>SMA</th>
<th>Supplier</th>
<th>Dimension</th>
<th>Ms (ºC)</th>
<th>Mf (ºC)</th>
<th>As (ºC)</th>
<th>Af (ºC)</th>
<th>ΔT (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM495</td>
<td>NDC</td>
<td>Ø0.185mm</td>
<td>49.48</td>
<td>17.81</td>
<td>51.94</td>
<td>75.42</td>
<td>26</td>
</tr>
<tr>
<td>NTC05</td>
<td>@MT</td>
<td>Ø0.185mm</td>
<td>65</td>
<td>34</td>
<td>50</td>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>NTC05</td>
<td>@MT</td>
<td>Ø0.3mm</td>
<td>55</td>
<td>25</td>
<td>55</td>
<td>80</td>
<td>25-30</td>
</tr>
<tr>
<td>Ni₂₅Ti₃₇,Cu₂₅</td>
<td>-</td>
<td>2mm x 0.06mm</td>
<td>63.16</td>
<td>58.76</td>
<td>65.10</td>
<td>70.02</td>
<td>6.02</td>
</tr>
</tbody>
</table>

The transformation temperatures shown in Table 3-1 were measured using Differential Scanning Calorimetry, except for Ø0.3mm NTC05 which was taken off the supplier’s specifications. The abbreviations @MT and NDC are the names of companies that supply shape memory alloys, and they are @medical technologies N.V. and Nitinol Devices & Components, respectively.

Applying current just enough to reach the transformation temperature is a key way to use the SMA effectively. Too high a current will simply overheat the wire and thus leading to longer cooling time. With this in mind, attempt is made to establish the relationship between the power supplied (electrically) and the amount of energy required to heat the SMA to a desired temperature (austenite finish temperature). The energy lost through convection is also considered. The resistance of the SMA with respect to temperature is important in establishing such a relation.

Another way to reduce the cooling time is to use SMA with narrow hysteresis. The shape memory properties of nickel-titanium can be readily modified by adding ternary elements which are chemically similar to nickel or titanium. Up to 30 percent copper, which is a
neighbour of nickel in the periodic table, may be substituted while retaining the same high
temperature austenite phase. Certain associated property modification, in particular a more
narrow transformation hysteresis and lower martensitic yield strength, are actually
beneficial for many applications [9]. Drastic reduction from 26 °C to 6 °C with 25% Cu
addition is achievable. NTC05 wire, purchased from the company @MT, is one such
SMA with Cu added; its ΔT can be as low as 15 °C. All these wires will be experimented
and compared for the amount of force generated and cooling time.

3.1.1 **SMA Wires Heat Treatment and Training**

All heat treatments will be conducted using a furnace a shown in Figure 3-1. The heat
treatments temperatures and duration for each type of SMA wire are tabulated in the Table
3-2. The fixture for holding the wire is shown in Figure 3-2.

**Table 3-2: Heat treatment**

<table>
<thead>
<tr>
<th>SMA</th>
<th>Supplier</th>
<th>Dimension</th>
<th>Heat Treatment Temperature</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM495</td>
<td>NDC</td>
<td>Ø0.185mm</td>
<td>580-600</td>
<td>20</td>
</tr>
<tr>
<td>NTC05</td>
<td>AMT</td>
<td>Ø0.185mm</td>
<td>580-600</td>
<td>20</td>
</tr>
<tr>
<td>NTC05</td>
<td>AMT</td>
<td>Ø0.3mm</td>
<td>580-600</td>
<td>20</td>
</tr>
<tr>
<td>Ni$<em>{25}$Ti$</em>{50}$Cu$_{25}$</td>
<td>-</td>
<td>2mm x 0.06mm</td>
<td>500</td>
<td>5</td>
</tr>
</tbody>
</table>
After heat treatment, the wire will be thermo-mechanically trained. Basically, there are two methods of training; the conventional training method using a furnace and a second method using resistive heating. These two methods will require the SMA to be heated up to 200°C, and then cooled to room temperature. Conventionally, the SMA wire will be strained to 12% elongation (this is performed on a tensile testing machine), followed by mounting the strained SMA onto a fixture, and then sent to the furnace for thermal cycling.
at 200°C for 50 cycles. The fixture with the strained wire will be taken in and out of the furnace at every 2 minutes interval; this is a very time consuming and tedious training method and the whole process will require 3 hours to complete! Another disadvantage using this method is the occurrence of spring back, after the strained SMA is removed from the clamps of the tensile testing machine. Therefore, the percentage of pre-strain will be smaller than the initial 12%.

On the other hand, using the resistive heating training method, the SMA wire will be strained to 12% on the Instron Tensile Testing Machine. Electrical connection to the SMA will then be wired and current will be passed through the SMA for a calculated period of time followed by allowing it to cool. All these are done automatically by the BASIC Stamp micro-controller (the specification of BASIC Stamp can be found in Appendix A1), while the SMA wire is still clamped at the Instron Machine. Thus, this implies that no spring back will occur. The approximate time to heat the wire to 200°C during thermal cycling and to cool the wire back to room temperature was estimated using the heat balance equation (discussed in Section 3.1.3). Usually the time required to heat the SMA wire of Ø0.185mm is only 0.75 to 1.2 seconds, followed by a 15 seconds interval for cooling. Therefore, it will only require approximately 27 minutes to complete 100 thermal cycles. The process of the thermal cycling using resistive heating will be discussed in detail as follows.
3.1.2 *Thermo-mechanical training by resistive heating for two-way shape memory effect*

The SMA wire will be first strained to 12% elongation, using very small strain rate (0.241mm/min to 0.6mm/min). This is done at the Instron machine as shown in Figure 3-3.

![Figure 3-3: SM495 wire clamped onto Instron machine’s vice](image)

Figure 3-3: SM495 wire clamped onto Instron machine’s vice

Figure 3-4 and Figure 3-5 showed curves obtained during one such straining process.

![Figure 3-4: 12% straining curve for SM495](image)
Both curves exhibit similar trend, though not as significant as the graph shown in Chapter 2, Figure 2-3, the onset of martensite detwinning, fully detwinned martensite and elastic deformation of detwinned martensite were observed.

BASIC Stamp micro-controller is used to control the current for heating and cooling. A hundred cycles of heating and cooling is programmed. The current is limited to 0.9A for the smaller diameter wires (Ø0.185mm). The following two plots showed the load (N) versus time (seconds) graph obtained for Ø0.185mm SM495 wire and NTC05 wires respectively during the thermal cycling.
Chapter 3: Heat Treatment, Thermo-mechanical Training and Measurement of SMA

Figure 3-6: Load versus time plot for SM495 wire training

Figure 3-7: Load versus time plot for NTC05 wire training

From the two plots, it was observed that a similar characteristic occurred during training; the initial few pulses would indicate higher force generation by the wires, subsequently the force would reduce until a near constant value of 11N (SM495 wire) and 11.5N (NTC05 wire) was obtained. This was observed to be more prominent in Ni-Ti wire.
Chapter 3: Heat Treatment, Thermo-mechanical Training and Measurement of SMA

The current required for heating is calculated using Ohm’s Law [38], which is shown in Equation (1).

\[ \text{Current} = \frac{\text{Voltage}}{\text{Resistance}} \]  

(1)

Usually, an additional resistor is required to limit the current passing through the SMA wire, for example an additional resistor of 5.6\(\Omega\) is added in series with the SMA wire (in this case, the SMA resistance is measured to be 7.7\(\Omega\)) to obtain a current value of approximately 0.9A.

The heating and cooling times, which are input into the micro-controller, can be approximated using heat balance equation, and these calculations are discussed in the following Section.

3.1.3 Approximation of the time for heating and cooling

If a current is passed through a resistive element, in this case SMA wire, the wire will be heated to a temperature \(T\), which is greater than the temperature of the surrounding fluid (air). The wire temperature \(T\) and resistance \(R\) depend on the balance between electrical power \((i^2 R)\) and the rate of overall convection heat transfer between the wire and air. The heat balance equation [39] for heating is shown in Equation (2):

\[ i^2 R - hA(T_c - T_v) = \rho V C_p \frac{dT}{dt} \]  

(2)
Chapter 3: Heat Treatment, Thermo-mechanical Training and Measurement of SMA

Where:

- $i$ - current passing through SMA in A
- $R$ - resistance of SMA in $\Omega$
- $A$ - Surface area of SMA in $m^2$
- $T_o$ - Initial temperature in K
- $T_f$ - Final temperature in K
- $\rho$ - Density of SMA in $kg/m^2$
- $V$ - Volume of SMA in $m^3$
- $C_p$ - Specific heat capacity of SMA

Whereas for cooling, the equation is:

$$hA(T_f - T_o) = \rho VC_p \frac{dT}{dt}$$

The unknown parameter in the above equations is the convection coefficient ($h$); to obtain $h$, Rayleigh number ($Ra$), Nusselt number ($Nu$) must first be calculated using the following equations [40].

$$Ra = Gr \times Pr$$

$$Gr = \frac{g \cdot \beta (T - T_{\infty}) \cdot \varphi^3}{\nu^2}$$

Therefore;

$$Ra = \frac{g \cdot \beta (T - T_{\infty}) \cdot \varphi \cdot Pr}{\nu^2}$$
Where \( Gr \) - Grashof number
\( Pr \) - Prandtl number
\( g \) - Gravitational acceleration in \( \text{m/s}^2 \)
\( \beta \) - Thermal expansion coefficient
\( T_i \) - Initial temperature of wire in K
\( T_{\text{atm}} \) - Ambient temperature in K
\( \phi \) - Diameter of SMA wire in m
\( \nu \) - Kinematic viscosity in \( \text{m}^2/\text{s} \)

Nusselt number for wires would then be calculated using Equation (7) as shown below.

\[
Nu = 0.6 + \left[ \frac{0.387 \times Ra^{1/6}}{1 + \left( \frac{0.559}{Pr} \right)^{9/16}} \right]^{2/3} \tag{7}
\]

Whereas Nusselt number for ribbon was calculated using Equation (8).

\[
Nu = 0.678 \times Ra^{1/4} \times \left( \frac{Pr}{0.952 + Pr} \right)^{1/4} \tag{8}
\]

Equation (7) was obtained from [41], while Equation (8) was obtained from [42]. All the calculated values were tabulated in the following two tables.
Table 3-3: Heat balance equation parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Ø0.185mm SM495 AF = 73°C</th>
<th>Ø0.185mm NTC05 AF = 77°C</th>
<th>Ø0.3mm NTC05 AF = 77°C</th>
<th>2mm x 0.06mm Ni25Ti50Cu25 AF = 71°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Expansion Coefficient, β (1/K)</td>
<td>3.1399E-03</td>
<td>3.1422E-03</td>
<td>3.1214E-03</td>
<td>3.1491E-03</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m.K)</td>
<td>0.02756</td>
<td>0.02754</td>
<td>0.027695</td>
<td>0.027485</td>
</tr>
<tr>
<td>Kinematics Viscosity, μ (m²/s)</td>
<td>17.6151E-06</td>
<td>17.5903E-06</td>
<td>17.8136E-06</td>
<td>17.5159E-06</td>
</tr>
<tr>
<td>Prandtl No.</td>
<td>0.7105</td>
<td>0.7105</td>
<td>0.7104</td>
<td>0.7106</td>
</tr>
<tr>
<td>Rayleigh No.</td>
<td>0.019</td>
<td>0.014</td>
<td>0.065</td>
<td>2.475E-04</td>
</tr>
<tr>
<td>Nusselt No.</td>
<td>0.587</td>
<td>0.574</td>
<td>0.646</td>
<td>0.069</td>
</tr>
<tr>
<td>Heat Transfer Coefficient, h (W/m²K)</td>
<td>87.471</td>
<td>85.522</td>
<td>59.618</td>
<td>32.443</td>
</tr>
</tbody>
</table>

Table 3-4: Theoretical cooling time of SMA

<table>
<thead>
<tr>
<th></th>
<th>300mm long, Ø0.185mm SM495 Trained for 100 Cycles</th>
<th>300mm long, Ø0.185mm NTC05 Trained for 100 Cycles</th>
<th>300mm long, Ø0.3mm NTC05 Trained for 100 Cycles</th>
<th>Ni25Ti50Cu25 30mm long, 2mm x 0.06mm 6% Strain</th>
<th>300mm long, Ø0.185mm Ni25Ti50Cu25 6% Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Convection Coefficient (W/m²K)</td>
<td>87.471</td>
<td>85.522</td>
<td>59.618</td>
<td>32.443</td>
<td>82.121</td>
</tr>
<tr>
<td>Theoretical Cooling Time from AF to MF (s)</td>
<td>4.755</td>
<td>2.672</td>
<td>6.458</td>
<td>4.069</td>
<td>1.276</td>
</tr>
</tbody>
</table>

The detail calculation can be found in Appendix A2. The theoretical cooling time for Ni25Ti50Cu25, which was assumed to be available in wire form of Ø0.185mm was shown in the fifth column of Table 3-4.
Chapter 3: Heat Treatment, Thermo-mechanical Training and Measurement of SMA

An assumption that the properties (density and specific heat capacity) of Ni$_{25}$Ti$_{50}$Cu$_{25}$ were similar to NTC05 was made, and the theoretical cooling time for Ni$_{25}$Ti$_{50}$Cu$_{25}$ in wire form of Ø0.185mm was calculated to be 1.276 seconds. Therefore, it was shown theoretically that alloying with copper resulted in a quicker cooling time (3.7 times faster than SM495), and the actuation rate could be improved to 0.784Hz. This was compared to 0.295Hz that was achievable by SM495 of Ø0.185mm. (These actuation rates were calculated by taking the reciprocal of the cooling time.)

The heat balance equation only took into account the specific heat capacity and density of the SMA, which were usually the same for SM495 and NTC05. In order to take into account the hysteresis of each SMA, the A$_f$ and M$_f$ temperatures must be known, and these temperatures were easily determined using DSC (discussed in the next section).

These estimated heating and cooling time will then be programmed into the BASIC Stamp micro-controller. This program can be used for resistive training of SMA wires and with some modifications; it can also be used for controlling the wires to deflect the flap. The flowchart showing the sequence for training is shown in Figure 3-8. The flowchart for a simple control of actuation is shown in Figure 3-9; the top wire(s) would be heated for a pre-determined number of seconds, followed by cooling and heating of the bottom wire(s). These programs can be in Appendix A3.
Start – Switch pushbuttons to ‘ON’ to initiate the program

Heat wire – Pulse set to ‘1’ to trigger MOSFET to heat wire for a pre-determined time

Cool wire – Pulse set to ‘0’ to cut the MOSFET

Has the number of cycles reached?
If ‘Yes’, end program.
If ‘No’, continue.

Figure 3-8: Flowchart for training

Start – Switch pushbuttons to ‘ON’ to initiate the program

Heat top wire – Pulse set to ‘1’ to trigger MOSFET to heat wire for a pre-determined time

Cool top wire – Pulse set to ‘0’ to cut the MOSFET

Heat bottom wire – Pulse set to ‘1’ to trigger MOSFET to heat wire for a pre-determined time

Cool bottom wire – Pulse set to ‘0’ to cut the MOSFET

Has the number of cycles reached?
If ‘Yes’, end program.
If ‘No’, continue.

Program end.

Figure 3-9: Flowchart for simple actuation
3.1.4  **Differential Scanning Calorimeter (DSC)**

Differential scanning calorimetry or DSC [43] is a thermo-analytical technique to examine thermal events in a sample by heating or cooling without mass exchange with its surroundings. The thermal events examined by DSC include solid phase transformation, glass transition, crystallization and melting. ‘Differential’ emphasizes that analysis is based on differences between sample material and a reference material in which the examined thermal events do not occur. A DSC instrument is designed to measure the heat flow difference between sample and reference. There are two widely used DSC systems: the heat flux DSC (the DSC in Smart Material Lab is based on this) and the power-compensated DSC. The heat flux DSC is also called ‘quantitative Differential Thermal Analysis’ because it measures the temperature difference directly and then converts it to heat flow difference. This conversion is accomplished by an algorithm in computer software installed in the system. The power-compensated DSC directly measures the enthalpy change of a sample during a thermal event. The transformation temperatures obtained for SM495 wires were presented in Table 3-5, while the results for the other three SMA were tabulated as shown in Table 3-6.
Table 3-5: Transformation temperatures of SM495

<table>
<thead>
<tr>
<th>SMA</th>
<th>Supplier</th>
<th>Dimension</th>
<th>Mf (ºC)</th>
<th>Ms (ºC)</th>
<th>As (ºC)</th>
<th>AT (ºC)</th>
<th>ΔT (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-Received SM495</td>
<td>NDC</td>
<td>Ø0.185mm</td>
<td>11.92</td>
<td>24.06</td>
<td>55.16</td>
<td>69.95</td>
<td>45.89</td>
</tr>
<tr>
<td>Annealed SM495 580ºC, 20min</td>
<td>NDC</td>
<td>Ø0.185mm</td>
<td>38.41</td>
<td>52.97</td>
<td>64.8</td>
<td>83.01</td>
<td>30.04</td>
</tr>
<tr>
<td>SM495 Trained for 100 Cycles</td>
<td>NDC</td>
<td>Ø0.185mm (Annealed at 580ºC)</td>
<td>21.79</td>
<td>50.61</td>
<td>58.95</td>
<td>80.19</td>
<td>29.58</td>
</tr>
<tr>
<td>SM495 Trained for 100 cycles</td>
<td>NDC</td>
<td>Ø0.185mm (Annealed at 600ºC)</td>
<td>22.53</td>
<td>39.57</td>
<td>58.21</td>
<td>73.40</td>
<td>33.83</td>
</tr>
</tbody>
</table>

Table 3-6: Transformation temperatures of other SMA

<table>
<thead>
<tr>
<th>SMA</th>
<th>Supplier</th>
<th>Dimension</th>
<th>Mf (ºC)</th>
<th>Ms (ºC)</th>
<th>As (ºC)</th>
<th>Af (ºC)</th>
<th>AT (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTC05 Trained for 100 cycles</td>
<td>@MT</td>
<td>Ø0.185mm</td>
<td>40.77</td>
<td>56.48</td>
<td>59.24</td>
<td>72.41</td>
<td>15.93</td>
</tr>
<tr>
<td>NTC05</td>
<td>@MT</td>
<td>Ø0.3mm</td>
<td>42.04</td>
<td>58.61</td>
<td>60.31</td>
<td>76.87</td>
<td>18.26</td>
</tr>
<tr>
<td>Ni&lt;sub&gt;25&lt;/sub&gt;Ti&lt;sub&gt;15&lt;/sub&gt;Cu&lt;sub&gt;25&lt;/sub&gt; Annealed at 500ºC for 5min</td>
<td>-</td>
<td>2mm x 0.06mm</td>
<td>53.48</td>
<td>66.74</td>
<td>58.88</td>
<td>71.13</td>
<td>4.39</td>
</tr>
</tbody>
</table>

The M<sub>s</sub> and M<sub>f</sub> temperatures of SM495 wire (resistive heating done for 50 cycles, Figure 3-10) were 23.68ºC and 8.89ºC respectively; this implied that full martensitic transformation was not achieved since M<sub>f</sub> was very much lower than room temperature. Thus the wire was not fully utilized. R-phase and a wide hysteresis (47.03ºC) were observed.
Figure 3-10: DSC result for SM495 after 50 cycles of training

Increasing the training cycles would help to improve the hysteresis, and this was shown in the next set of result where the training cycles were increased to 100 cycles. The $M_s$ and $M_f$ were observed to have shifted to 21.79°C and 50.61°C respectively. A hysteresis of 29.58°C was obtained. A merger of R-phase and the martensitic transformation was also observed. Figure 3-11 showed the DSC result.
Increasing the annealing temperature to 600°C (above the recrystallization temperature) would also help to increase the $M_f$ temperature for SM495 to above 20°C. Annealing temperatures below 600°C would result with a two-step transformation during cooling, but only one exothermic peak due to transition from austenite to martensite was observed for annealing temperatures above 600°C [44]. The DSC results for SM495 annealed at 600°C were shown in Figure 3-12.
Chapter 3: Heat Treatment, Thermo-mechanical Training and Measurement of SMA

Figure 3-12: DSC result for SM495, annealed at 600°C, after 100 cycles of training

It was also important to ensure that the annealing temperature was correct; this was experienced during the initial annealing of SM495 whereby the wire appeared to have two tones of colours (bluish and greenish) after the heat treatment. This was caused by uneven temperature distribution inside the furnace. The temperature indicator of the furnace indicated the temperature where the in-built thermocouple was located, thus the temperature of the SMA would be lower (or possibly higher) where the SMA was placed. This problem could be overcome by using a second thermocouple, placed as close as possible to the SMA, to monitor the temperature in the vicinity of the SMA during the heat treatment process.
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The DSC result for Ø0.185mm NTC05, Ø0.3mm NTC05, and Ni25Ti50Cu25 were shown in Figure 3-13, Figure 3-14 and Figure 3-15 respectively. Comparing with SM495, the hysteresis was very much narrower especially Ni25Ti50Cu25.

Figure 3-13: DSC result for Ø0.185mm NTC05 after 100 cycles of training

Figure 3-14: DSC result for Ø0.3mm NTC05 after 100 cycles of training
Two more DSC results for SM495 can be found in Appendix A4.

3.2 The Measurement Process

The SMA heating and cooling times, resistance and current passing through the wire are measured using two measurement methods. The first is a data acquisition system, National Instruments CompactDAQ (the details of this system can be found in Appendix A5). The second method makes use of the Instron tensile machine to log the force generated by the SMA as it heats and cools, and this will be log against time in seconds. These measurements will be made for all the SMA listed in Table 3-1.
3.2.1 National Instruments CompactDAQ

The change in temperature [as the SMA wire was being heated] was sampled by the NICompactDAQ at every 50 milliseconds. The thermocouple used was a Type K, AWG-36 with exposed junction, and with a bulb size of 0.127mm. This is actually a standard Type-K thermocouple, except it has a smaller bulb size of 0.127mm. This bulb size is selected to allow the thermocouple to be placed as close as possible to the smallest SMA of Ø0.185mm. Slow heating was performed with current ranging from 0.55 Ampere to 1.35 Ampere. The time taken to reach its A_f was set as the target temperature to cut off the power supply. To measure the resistance of the SMA, a shunt resistor of 0.1Ω was used to measure the current flowing through the circuit instead of using the 4-wire resistance measurement. This was because 4-wire resistance measurement using National Instruments CompactDAQ worked by passing an excitation current (very small value) through the specimen; unfortunately a high current ranging from 0.55 Ampere to 1.35 Ampere was passed through the specimen at the same time during heating, and it interfered with the measurement leading to a saturated value. The solution was to make use of a shunt resistor of very low resistance connected in series with the specimen, and the voltage across it was measured. With the known resistance value of 0.1Ω, the current was easily calculated.

3.2.2 Measurement using Instron tensile machine

To estimate the heating and cooling times; Instron Tensile machine 5548 with maximum capacity of 2kN was used. The SMA specimens (length: 30mm) were clamped onto the vice of the machine, and a small pre-tension was applied. Current was passed through the specimen to heat it, and the stress (or generated force) was monitored against time. The
stress (or force) would increase till it reached a maximum, then it would plateau, and this indicated that the maximum stress (or force) has been reached, in another word, transformation temperature $A_f$ has reached. The power supplied to the SMA would then be terminated to allow the SMA to cool. All these information were logged by the software of the tensile machine, which were plotted against time to allow the heating/cooling time to be estimated. (The data can be found in Appendix A6.)

To measure the recovery force against time, resistive heating of SMA wire will be used. The trained SMA wire will be installed onto the clamps of the Instron machine. The clamp region will be required to be insulated. Next, tension the SMA wire slightly to obtain a straight and taut SMA wire. The Instron tensile machine will then be set to register the force generation by the SMA wire during heating and cooling. Current is then passed through the SMA wire. To prevent overheating of the SMA wire, the current is limited to 1A or less. Lastly, obtain the log of SMA force versus time data.

The measured data will then be plotted to obtain two curves; the heating time versus time plot and power versus current plot. The heating time versus time plot will be curve-fitted and the equations thus obtained can be used for estimating the time taken required to heat the SMA wire to $A_f$. 

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3.2.3 Measurement result for SM495, NTC-05 and Ni$_{25}$Ti$_{50}$Cu$_{25}$

Figure 3-16: Heating time as a function of input current for Ø0.185mm NTC05, Ø0.3mm NTC05, Ø0.185mm SM495 and 2mm x 0.06mm Ni$_{25}$Ti$_{50}$Cu$_{25}$

Figure 3-16 showed a plot of heating time as a function of input current for trained SM495, NTC05, and annealed Ni$_{25}$Ti$_{50}$Cu$_{25}$. All the four specimens were 300mm in length. These data are curve-fitted to obtain an equation, which can be used to calculate the heating time to reach austenite finish temperature and this is shown in Figure 3-17. For example, the Lorentzian curve-fitted equation for Ø0.185mm, 300mm long SM495 wire was shown in Equation (9) with the coefficients of determination, $R^2$ of 0.99442, and for an input current of 800mA, the heating time ($t_{SM495,0.185,300}^{\text{NFA}}$) was calculated to be 3.5 seconds.

$$t_{SM495,0.185,300}^{\text{NFA}} = 1.3477 + \left[ \frac{2 \times 17315}{\pi} \right] \times \left[ \frac{131.91}{4(i - 393.33)^2 + 131.91^2} \right]$$  \hspace{1cm} (9)
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The Lorentzian curve-fitted equations for the other three SMA are as follows:

\[
I_{NTC05 \varnothing 0.185}^{900} = 2.3923 + \left( \frac{2 \times 2868.8}{\pi} \right) \times \left[ \frac{174.29}{4(i - 524.82)^2 + 174.29^2} \right] \\
(10)
\]

\[
I_{NTC05 \varnothing 0.3}^{900} = 2.1923 + \left( \frac{2 \times 3062.1}{\pi} \right) \times \left[ \frac{284.31}{4(i - 970.81)^2 + 284.31^2} \right] \\
(11)
\]

\[
I_{NiTiCu \varnothing 0.06}^{900} = 4.6043 + \left( \frac{2 \times 25958}{\pi} \right) \times \left[ \frac{128.03}{4(i - 838.44)^2 + 128.03^2} \right] \\
(12)
\]

Figure 3-17: Curve-fitted heating time as a function of input current for Ø0.185mm NTC05, Ø0.3mm NTC05, Ø0.185mm SM495 and 2mm x 0.06mm Ni_{25}Ti_{50}Cu_{25}
Figure 3-18 showed the variation in power as the input current was increased for the four types of SMA.

![Graph showing power variations](image)

Figure 3-18: Power variations as input current increased, for Ø0.185mm NTC05, Ø0.3mm NTC05, Ø0.185mm SM495 and 2mm x 0.06mm Ni$_{25}$Ti$_{50}$Cu$_{25}$

Both Ø0.185mm SMA exhibited similar power requirements, and with the power known, the power consumption to reach $A_f$ was calculated as shown in Table 3-7. The average cooling time and cooling rate for each SMA were also shown in Table 3-7, and it was shown that both Ø0.185mm SMA were able to cool from $A_f$ to $M_f$ in less than 3.5 seconds while Ni$_{25}$Ti$_{50}$Cu$_{25}$ required 3.713 seconds.
Table 3-7: Heating/cooling time and power calculation

<table>
<thead>
<tr>
<th>Force Generation (N)</th>
<th>Heating Time (s) (Current: 1A)</th>
<th>Power (Watts) (Current: 1A)</th>
<th>Power Consumption (KWh)</th>
<th>Average Cooling Time from Af to Mf (s)</th>
<th>Cooling Rate (°C/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300mm long, Ø0.185mm SM495 Trained for 100 Cycles</td>
<td>10.75</td>
<td>2.32</td>
<td>0.958 x 10^-5</td>
<td>3.388</td>
<td>12.694</td>
</tr>
<tr>
<td>300mm long, Ø0.185mm NTC05 Trained for 100 Cycles</td>
<td>6.5</td>
<td>2.73</td>
<td>1.049 x 10^-5</td>
<td>2.917</td>
<td>10.800</td>
</tr>
<tr>
<td>300mm long, Ø0.3mm NTC05 Trained for 100 Cycles</td>
<td>28</td>
<td>8.77</td>
<td>1.074 x 10^-5</td>
<td>6.085</td>
<td>5.752</td>
</tr>
<tr>
<td>Ni_25Ti_50Cu_25 30mm long, 2mm x 0.06mm 6% Strain</td>
<td>14</td>
<td>22.12</td>
<td>2.581 x 10^-5</td>
<td>3.713</td>
<td>4.715</td>
</tr>
<tr>
<td>Ni_25Ti_50Cu_25 30mm long, 2mm x 0.06mm Annealed</td>
<td>10.8</td>
<td>-</td>
<td>-</td>
<td>4.738</td>
<td>3.694</td>
</tr>
</tbody>
</table>

From this exercise, it was conclusive that using SMA of smaller diameter would allow better actuation rate; thus suggesting that Ø0.185mm SMA should be used for the actuation of the flap. The Ø0.3mm NTC05, though was generating a large force of 28N, would only allow a 0.164Hz actuation rate. Ni_{25}Ti_{50}Cu_{25} was very difficult to handle, this was because it was only available in thin ribbon form and it tends to break easily.

From both DSC and measurement results, it was shown that SMA having smaller hysteresis, e.g. NTC05 and Ni_{25}Ti_{50}Cu_{25}, cooled down faster. However, the difference was not significant for Ø0.185mm SM495 and Ø0.185mm NTC05, and the force generated was by NTC05 was 39.5% lower than that of SM495. In addition, the cooling rate was dominated by SM495 with a value of 12.694 degrees Celsius per second. Therefore, Ø0.185mm SM495 was selected as the actuator for the wing prototype.
Chapter 3: Heat Treatment, Thermo-mechanical Training and Measurement of SMA

One observation made during the measurement using National Instruments CompactDAQ was the response of the thermocouple; as the current increased, the time taken for the SMA to heat up could be instantaneous causing some time to elapse before the thermocouple completed the change [39]. This was very noticeable for small diameter SMA measured using these thermocouples. These measurements were repeated and compared using the force versus time method (Instron tensile machine), and since heating were adjustable by the input current, only the cooling time results were taken in consideration during the averaging calculation for all SMA.

Finally, both theoretical and measured cooling time for the SMA were compared and shown in Table 3-8.

Table 3-8: Comparison of theoretical and measured cooling time

<table>
<thead>
<tr>
<th></th>
<th>Theoretical Cooling Time from AF to MF (s)</th>
<th>Measured Cooling Time from AF to MF (s)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300mm long, Ø0.185mm SM495 Trained for 100 Cycles</td>
<td>4.755</td>
<td>3.388</td>
<td>40.363</td>
</tr>
<tr>
<td>300mm long, Ø0.185mm NTC05 Trained for 100 Cycles</td>
<td>2.672</td>
<td>2.917</td>
<td>8.389</td>
</tr>
<tr>
<td>300mm long, Ø0.3mm NTC05 Trained for 100 Cycles</td>
<td>6.458</td>
<td>6.085</td>
<td>6.129</td>
</tr>
<tr>
<td>Ni25Ti50Cu25 30mm long, 2mm x 0.06mm 6% Strain</td>
<td>4.069</td>
<td>4.715</td>
<td>9.606</td>
</tr>
<tr>
<td>Ni25Ti50Cu25 300mm long, Ø0.185mm 6% Strain</td>
<td>1.276</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The percentage error for both NTC05 and Ni25Ti50Cu25 are below 10%, except SM495 which is 40.363%! The source of error is likely encountered during the measurement process. These errors include actual sensor and instrument error, changes or unknowns in measurement system operating conditions, such as power settings and environmental conditions that affects system performance, and sensor installation effects on the measurement [45].
Shape memory alloys are temperature sensitive; therefore the measurement results are easily affected by the environmental condition especially the ambient temperature. The measurement for SM495 was performed in an air-conditioned environment, with the moving air directly flowing across the SMA. Therefore, the time taken to cool (to $M_f$) decreased. However, the theoretical calculation based on forced convection was not performed because the velocity of the air flowing across the SMA was not known. The air velocity was required for the determination of the Reynolds number.

Another possible cause of the high error value was the discrepancy that may occur during annealing and training, leading to non-uniform characteristic of the shape memory effect.

### 3.3 Chapter Summary

Shape memory alloy heat treatment and thermo-mechanical training are covered in this chapter; both furnace and resistive heating training methods are described. Differential scanning calorimetry was used to measure the transformation temperatures of the SMA after heat treatment and thermo-mechanical training. The results were compared and studied. Data acquisition was performed to obtain the heating & cooling temperature, resistance and voltage across of the SMA. It was conclusive that Ø0.185mm SMA and SMA with smaller hysteresis would cool faster, and it was also shown through theoretical calculation that $\text{Ni}_{25}\text{Ti}_{30}\text{Cu}_{25}$ (if it was available in cylindrical form of Ø0.185mm) would be able to cool in 1.276 seconds. With such a cooling ability, it was capable of achieving a much higher actuation frequency of 0.784Hz.
Chapter 4: The Shim-based Wing Prototype

Phase 2 will be covered in this chapter. The design flow and testing process is shown in Figure 4-1. Flexible skin and a mechanism to engage/disengage SMA during heating/cooling are also explored and the findings will be discussed.

Figure 4-1: Design flow for wing prototype
Chapter 4: The Shim-based Wing Prototype

The rib prototypes based on concept #1 & #2 were fabricated. Initial tests using SM495 wires revealed that rib concept #2 was more flexible and was able to achieve better deflection. After the successful demonstration of the rib based on concept #2, the wing prototype was fabricated. Both glass fibre composite-silicone rubber hybrid skin and overlapping glass fibre composite skin were also fabricated. Lastly, the engage-disengage mechanism was designed and studied.

4.1 Rib Conceptual Designs

Figure 4-2 shows the three types of rib that were conceptualized and modeled using SolidWorks (computer-aided design software).

Conventional hinge is replaced by metallic shim for concept #1 and #2. Since the shim has to withstand aerodynamic load and actuation load, SK-5 high tensile strength spring steel is selected. The mechanical properties of SK-5 can be found in Appendix B1. The neutral position of these two concepts is achieved through the shim’s ability to spring back when the actuation force from the SMA is removed, in another word, it is self resetting. However, there are two drawbacks. The SMA actuator is required to work against the
stiffness of the shim, and in order to keep the flap in deflected position, the SMA actuator must be kept heated. Lastly, the difference between the two concepts lies in the stiffness; concept #2 is more flexible and this is due to the fact that it has a longer effective shim length. The detail design and tests of the shim version will be presented in the subsequent sections.

Concept #3 is a hinged rib design. Since this is hinged, there will only be frictional forces at the hinge point, in contrast to the shim version whereby the SMA actuator has to work against the shim’s stiffness. An additional locking system will be required to lock the flap in the desired position. Though this concept is not self resetting, the locking system helps to reduce the power requirement, when compared to the shim version that makes use of a heated SMA actuator to sustain the desired deflection. The detail design and tests of the hinged version is presented in Chapter 5.

The material selected for making these rib prototypes is Delrin; this material is used because it is electrically non-conductive and has a melting temperature of around 175°C. The mechanical properties of Delrin can be found in Appendix B2. However, sandwich structure using glass fibre – wood (or structural foam) core can be considered for the actual application in order to achieve sound structural integrity, and lighter weight.
4.2 Sizing and Analyses

4.2.1 Hinge moment calculation

Based on the design criteria presented in Chapter 1, the dynamic pressure of the free stream, denoted by ‘q’, is calculated using the Equation (13) [46]:

\[ q = \frac{1}{2} \times \rho \times V_{\text{max}}^2 \]  

(13)

Where \( \rho \) is the density of air in kg/m\(^3\), and \( V_{\text{max}} \) is the velocity in m/s.

The total lift force (L) acting on the flap is then calculated using Equation (14) [46].

\[ L = q \times C_{\text{Lactuate}} \times S \]  

(14)

Where L is the lift force in N, q is the dynamic pressure, and \( C_{\text{Lactuate}} \) being the flap lift coefficient.

The values of \( \rho, V_{\text{max}}, C_{\text{Lactuate}} \) and S can be found in Chapter 1, Table 1-2.

To calculate the hinge moment, a triangular load distribution is assumed, acting along the chord-wise direction of the flap as shown in Figure 4-3.
Chapter 4: The Shim-based Wing Prototype

To determine the load per unit, the area of the triangular distribution is equated to the lift force (L).

\[ L = \frac{1}{2} \times \text{Length} \times \psi \]  \hspace{1cm} (15)

Where Length equals to 100mm, and \( \psi \) is the load per unit length (N/m).

Finally by summation of force and moment, the reaction force (Ra) and hinge moment (HM) are calculated to be 18.86051N and 0.628684Nm respectively. These values were calculated with a safety factor of 1.5. The hinge moment for zero flap deflection is calculated to be 0.471513Nm, using the same set of equations as shown above.

4.2.2 Shim Thickness Sizing

With the hinge moment known, the thickness of the shim was sized using both calculation and finite element analysis (FEA). The rib was designed to handle a fraction of the hinge moment. Therefore, the shim thickness would varied with the total number of ribs (shim thickness increased as number of ribs decreased), likewise for the SMA wires (number of wires increased as number of ribs decreased). In this way, the rib could be independently designed. For this project, a ten ribs design would be considered and the minimum shim thickness was calculated to be 1.309mm using Equation (16) [47].

\[ Y_A = \frac{-W}{6EI} \left[ (2l^3) - (3l^2a) + a^3 \right] \]  \hspace{1cm} (16)

Where \( Y_A \) is the deflection in mm, \( W \) is the applied load in N, \( E \) is the modulus of elasticity of shim in N/mm\(^2\), \( I \) is the area moment of inertia of the shim cross-section in mm\(^4\), \( l \) is the effective length of the shim in mm, and \( a \) is the distance measured from the free end of the shim in mm.
Chapter 4: The Shim-based Wing Prototype

The FEA was conducted to verify against the calculated thickness using Equation (16). It was simplified and only the load to create the hinge moment for zero flap deflection was applied; all other possible forces were neglected. It was realized that in order for the shim to be able to sustain the hinge moment at zero flap deflection, a minimum thickness of 1.5mm must be used (which was close to the calculated thickness). The FEA result was shown in Figure 4-4, whereby the thickness was increased until the deflection at the trailing edge tip became less than 1mm.

![Figure 4-4: Finite element analyses, vertical displacement and deflected angle versus shim thickness; the vertical axis represents both displacement in mm and deflected angle in degree (the deflected angle in this plot implies undesired deflection due to aerodynamic load at neutral position)](image)

Figure 4-5 showed the theoretical bending moment, calculated using Equation (16), and plotted against the deflection angle for various shim thicknesses. From the graph, it was observed that the bending moment would increase as the deflection angle increased, and this was very prominent for thicker shim (1mm and above). Therefore, a very large force from the SMA actuator must be generated if the 1.5mm thick shim was used.
Large diameter SMA wires or multiple strands of SMA wires (small diameter) must be used, if a large force was required. However, the response of the actuation would be compromised if large diameter SMA wires were used. This was because the larger diameter SMA wires would require a longer time to cool, as shown in Appendix A2. On the other hand, using multiple wires at this stage of the project would complicate the actuator design because it would involve very complex electrical wiring that required isolation (to prevent short-circuit). Therefore, reducing the shim thickness would be a prudent choice to allow the demonstration of the SMA actuator without complicating the design with complex controlling, or with the response compromised. Once the concept of actuation has been proven and demonstrated, the shim could be replaced since it was a modular design, and SMA (or multiple SMA) that were able to produce higher force would be used.
4.2.3 **SMA Anchoring Positions on Demonstration Rib**

The SMA application for this project is classified as work production (Chapter 2, Section 2.1.2). Work is done when the SMA exerts a force to lift the flap, and these SMAs are trained to achieve two-way shape memory effect (TWSM). The engineering applications of TWSM are designed to take advantage of the added feature of spontaneous shape change on cooling. Briefly summarized, the main feature of TWSM that may be exploited in an application is the fact that the component will deflect in one direction upon heating, and in the opposite direction upon cooling [9]. This spontaneous shape change during cooling will be assisted by the shim to bring the flap back to the neutral position.

Four locations on the movable part of the rib are identified for anchoring one end of the SMA, as shown in the Figure 4-6. The other end of the SMA is secured near the leading edge of the rib.

![Figure 4-6: Four anchoring positions for SMA](image)

The maximum force that each Ø0.185mm SMA could generate was 10N, and this was calculated based on the yield stress of 370MPa (austenite phase). The external skin that would increase the stiffness of the overall assembly was not considered in the above
calculation. By taking moment about point ‘P’, the theoretical moment generated by each SMA wire combination was calculated as shown in Table 4-1. The detail calculation can be found in Appendix B3. These theoretical moments were then compared with Figure 4-5 to obtain the maximum deflection angle achievable and the maximum shim thickness that the wire combination could handle (column 3 of Table 4-1). However with multiple wires, it would complicate the initial demonstration with too many SMA wires to actuate per side, and each wire must also be electrically isolated to prevent short circuit when the wire contacted each other. Therefore, only wire combinations 1 and 3 would be used since they were easier to manage.

**Table 4-1: Ø0.185mm SMA Wires Combination - Moment Calculation**

<table>
<thead>
<tr>
<th>Wire Combination</th>
<th>Calculated Moment</th>
<th>Achievable Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination 1 (per rib) 1 wire at Pos. C only</td>
<td>157.4Nmm</td>
<td>Unable to deflect shim</td>
</tr>
<tr>
<td>Combination 2 (per rib) 1 wire at Pos. A, 1 wire at Pos. B</td>
<td>286.8Nmm</td>
<td>Up to 6º using 0.6mm thick shim</td>
</tr>
<tr>
<td>Combination 3 (per rib) 2 wires at Pos. C</td>
<td>314.8Nmm</td>
<td>Up to 6.7º using 0.6mm thick shim</td>
</tr>
<tr>
<td>Combination 4 (per rib) 1 wire at all positions except Pos. D</td>
<td>575.8Nmm</td>
<td>Up to 12.5º using 0.6mm thick</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Up to 7.6º using 0.7mm thick shim</td>
</tr>
<tr>
<td>Combination 5 (per rib) 1 wire at all positions except Pos. A</td>
<td>607.2Nmm</td>
<td>Up to 13.3º using 0.6mm thick</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Up to 8.4º using 0.7mm thick shim</td>
</tr>
<tr>
<td>Combination 6 (per rib) 1 wire at all positions</td>
<td>736.6Nmm</td>
<td>Up to 10º using 0.7mm thick shim</td>
</tr>
</tbody>
</table>

Table 4-1 showed that only shim with thickness up to 0.7mm are deflectable using small diameter SMA (Ø0.185mm in this case). The largest angles achievable were 13.3º and 10º, using 0.6mm and 0.7mm thick shim respectively. These angles were able to satisfy the
requirement stated in Chapter 1, Table 1-2. The calculations shown in Table 4-1 confirmed the fact that SMA of small diameter (Ø0.185mm) were unable to generate sufficient force (or moment) to overcome the stiffness of thick shims (1mm and above in thickness).

A shim thickness of 0.6mm was selected since it required the least force to flex, and it was shown in Table 4-1 that a deflection angle of $6.7^\circ$ could be achieved using wire combination 3. The applied loading, finite element model and von Mises stress result of the simplified model with 0.6mm thick shim were shown in Figure 4-7, Figure 4-8 and Figure 4-9 respectively. The shim area that was embedded into the main rib was considered as a fixed constraint, and the maximum von Mises stress was 493.7MPa. The stress was below the yield strength of the shim material.
Figure 4-9: von Mises plot for 0.7mm thick shim analysis

4.3 Rib Fabrication and Test

Rib concepts 1 and 2 were fabricated and assembled as shown in Figure 4-10 and Figure 4-11. Figure 4-12 showed the deflected rib concept #2.
The initial concept demonstration of the rib was done using wire combination 1, and plastic (polyurethane) shim was used. Figure 4-12 showed the actuation, achieving an angle of 16°.

Figure 4-12: Deflected rib concept #2 using plastic shim

Rib concept #2 was further tested using metallic shim (0.6mm thick) and similar test was conducted using wire combination 3. With the increased stiffness of the shim, the angle of deflection was reduced drastically to 7.4° as shown in Figure 4-13. This angle was close to the theoretical angle of 6.7° shown in Table 4-1.

Figure 4-13: Deflected rib concept #2 using SK-5 shim
Chapter 4: The Shim-based Wing Prototype

The above tests proved that the curves shown in Figure 4-5 were valid since the angle of deflection was drastically reduced from 16° to 7.4° when the stiffness was increased. The installation of the flexible skin at a later stage of the project would cause the overall wing assembly stiffness to increase further, and these tests were discussed in a later section.

4.4 Wing Prototype Fabrication and Assembly

Rib concept #2 is selected after realizing that it required a lower actuation force as compared to rib concept #1 due to a longer effective shim length. The model of the wing prototype is shown in Figure 4-14 with a span of 150mm. Two ribs will be used with four aluminum rods as spars and polystyrene foam will be used to support the skin at the trailing edge. Glass fibre will be used as skin for the non-movable portion of the wing prototype while a flexible skin will be applied to the trailing edge to accommodate the change in shape during actuation.

Figure 4-14: Model of wing prototype with GF-SR skin concept
Chapter 4: The Shim-based Wing Prototype

4.4.1 Rib Internal Construction

The prototype was fabricated and assembled as shown in Figure 4-15 with two ribs, four aluminum rods as spars and polystyrene foam to support the skin at the trailing edge. Flexible skin would be installed at a later stage and this was discussed in Section 4.5 and 4.6.

Figure 4-15: Internal construction of the prototype

4.4.2 Load test on wing prototype

The load test was conducted to verify the strength of the rib assembly as shown in Figure 4-16, and the result for concept #2 was shown in Figure 4-17, with 0.3mm thick shim and 0.6mm thick shim to determine the actual moment to deflect up to 15°. No apparent material distress was observed at the maximum deflection of 15°.

Figure 4-16: Structural load test on the rib
Chapter 4: The Shim-based Wing Prototype

Figure 4-17: Rib structural load test result with load applied 32.5mm away from the trailing edge

A comparison was made between the theoretical and experimental results for 0.6mm thick shim (Figure 4-18). A straight line was observed for the theoretical values. This was because the shim was still within the elastic zone of the material. However, a non-linear behaviour was observed from the load test results.

Figure 4-18: Comparison between theoretical and experimental load test result for 0.6mm thick shim
Chapter 4: The Shim-based Wing Prototype

The maximum non-linearity, expressed as a percentage of full scale deflection, i.e. full scale of the span \([39]\) can be calculated using Equation (17).

\[
\text{Max}_{\text{nonlinear}} = \frac{N}{O_{\text{max}} - O_{\text{min}}} \times 100\% \quad (17)
\]

Where \(N\) is the maximum difference between the measured and calculated values, \(O_{\text{min}}\) is the minimum \(y\)-value (minimum force value) and \(O_{\text{max}}\) is the maximum \(y\)-value (maximum force value). This was calculated to be 18\%. This non-linear behaviour was caused by slippage occurring at the shim-to-rib interface during the loading. Therefore, bonding of the shim to the rib must be done to prevent the slippage.

4.5 Flexible Skin Designs

One of the major considerations to achieve a smooth camber change is the skin, which must be flexible. Two types of flexible skins will be explored and they are silicone rubber-glass fibre composite hybrid skin and overlapping glass fibre skin.

4.5.1 Glass Fibre Composite-Silicone Rubber Hybrid Skin (GF-SR hybrid skin)

Silicone rubber sheet (0.5mm thick) will be applied to the trailing edge to accommodate the change in shape during actuation. This version of skin will combine the stiffness from the glass fibre composite and stretchable properties from the silicone rubber sheet. A hybrid glass fibre-silicone rubber skin fabrication will be attempted and the most suitable adhesive to bond the two materials together will be explored.

4.5.2 Overlapping Glass Fibre Skin (O-GF skin)

The change in shape during actuation is achieved by having glass fibre composite skin sliding over each other as shown in the below figure.
Figure 4-19: Schematic of overlapping glass fibre composite skin

The top and bottom composite skins will slide in and out of the trailing edge casement during actuation. A lower force to actuate the flap can be achievable since the SMA only requires to overcome the frictional force between the composites as compared to the silicone glass hybrid version whereby the SMA is required to overcome the tension in the stretched silicone rubber.

4.5.3 Glass Fibre-Silicone Rubber Flexible Skin Fabrication Process

The GF-SR hybrid skin was fabricated in two steps:

1. Two plies of glass fibre cloth were laid using epoxy (mixed with hardener). A flat piece of acrylic was used as the mould. Wax was first applied onto the acrylic and polished till a smooth surface was obtained. The first ply of glass fibre cloth was laid; the epoxy mixture was evenly spread and the second ply was laid over the first. More epoxy mixture was applied. A plastic sheet was then placed onto the two plies and excess epoxy mixture was pushed out using a patty knife. Finally the composite was clamped together and left to cure for 24 hours.

2. After the glass fibre composite was cured, it was cut to the required size. Silicone rubber of 0.5mm thick was measured and cut. Room temperature
vulcanizing silicone (RTV silicon, a silicone adhesive) was used to bond the silicone rubber sheet to the glass fibre composite. The completed skin was finally clamped together and left to cure for another 24 hours. The assembled hybrid skin was shown in Figure 4-20.

Figure 4-20: Prototype installed with GF-SR hybrid skin

Three concepts of hybrid glass fibre-silicone rubber sheet were experimented as shown in Figure 4-21.

Figure 4-21: Three concepts of hybrid skin

Hybrid (i) was the very first concept whereby a fabric mesh was embedded in RTV silicone (high temperature type). The fabric mesh was used to sustain a small percentage
of the aerodynamic loads and at the same time, to provide the necessary span wise flexibility with the mesh oriented at 45°. The ability to withstand pressure loading can be improved by replacing the fabric mesh with a metallic mesh (also shown in the above figure).

Hybrid (ii), another hybrid skin whereby glass fibre composite was directly bonded to 0.5mm thick silicone rubber sheet. A small interval between glass fibre composite was to allow the chord wise stretch of the silicone rubber sheet. These fibre glass composites were able to provide very good flexural bending and axial stiffness.

Hybrid (iii), similar to (ii) but with increased distance between the glass fibre composite interval; the increased interval was to reduced the axial stiffness of the hybrid skin. The lower axial stiffness would allow a lower actuation force to deflect the prototype.

4.5.4 Overlapping Glass Fibre Skin

The overlapping skin was basically made up of plain glass fibre composite. Therefore the procedure to make the composite skin was the same (described above). Figure 4-22 showed the overlapping glass fibre skin.

![Overlapping Glass Fibre Skin](image)

Figure 4-22: Prototype installed with O-GF skin
4.6 Actuation Tests

The wing prototype with 0.6mm thick shim, assembled with GF-SR hybrid skin was finally tested using wire combination 1. Corresponding to the earlier calculation shown in Table 4-1, the resulting flap deflection angle was very small (less than 2°); this was due to the high stiffness achieved with the highly stretched silicone rubber (overall stretching of 10mm of silicone) of GF-SR skin. The high overall assembly stiffness resulted in insufficient force generation by the single SMA wire.

The load test was conducted again for the prototype assembled with GF-SR skin, and it was observed that the applied load was increased by an average of 1.86 times. Two solutions to the above problem were then proposed and tested. The first attempt was to reduce the overall assembly stiffness; this was achieved by reducing the stretch in the skin to 5mm. The deflection test was conducted again using the single wire arrangement and the angle of deflection was slightly improved to 2°. With this attempt, it was concluded that a single SMA wire per rib was insufficient to actuate the prototype. The second attempt was to increase the number of SM495 wires and wire combination 3 was tested (Table 4-1). The resulting angle of deflection was improved further to 5.2° (9mm vertical displacement) and Figure 4-23 showed the deflected prototype.
Similar tests were done with the wing prototype assembled with O-GF skin. The O-GF skin offered a lower overall stiffness, thus the resulting flap deflection of $5^\circ$ was easily achieved, using wire combination 3.

With the above demonstrations, it was verified that deflection angle would be affected by stiffness of the prototype assembly, and this led to the need for design improvement with the following two points to consider.

The first point is the need of larger diameter or multiple SMA wires to overcome the stiffness for thicker shims. However, large diameter SMA wires will reduce the actuation rate as they required a longer time to cool. Multiple SMA wires, on the other hand, required complex control. The next point is related to the shim thickness, if thinner shims are used, e.g. 0.6mm thick shim or plastic shim, a locking mechanism to lock the flap at desired position will be required.
Chapter 4: The Shim-based Wing Prototype

To address point number 1, the prototype was tested using a larger diameter SM495 (Ø0.5mm). The resulting deflection was 15°, but it was achieved at the expense of much slower cooling rate. Figure 4-24 showed the deflection.

![Figure 4-24: Large deflection achieved using Ø0.5mm SM495](image)

To address point 2, the SMA wires were kept heated to sustain the flap in the deflected position, instead of a locking mechanism. However, this was done at the expense of higher power consumption.

4.7 Engage-Disengage Mechanism Actuation Test

Improvement in actuation frequency might be achievable by incorporating a mechanism, which will engage/disengage the SMA wires during heating/cooling. The idea is to disengage the SMA wire during cooling in order to allow the actuating wire to perform work without having to overcome the residual force generated by the cooling wire. A conceptual design is shown in Figure 4-25.
Chapter 4: The Shim-based Wing Prototype

Figure 4-25: Concept of EDE mechanism

SMA wire at the top was shown ‘engaged’ while the bottom wire was loose in the top diagram; the reverse was shown in the bottom diagram. The engaged SMA wire will then be heated to perform work without hindrance from the opposing wire. The activation of the mechanism is left open; either smart actuation (using SMA) or mechanical actuation can be adopted. A computer-aided design (CAD) model, using SMA is shown in Figure 4-26.

Figure 4-26: EDE mechanism with interconnected SMA wires
This CAD model will provide a better visualization of the working principle behind the concept. The flap SMA is interlinked to the EDE lever as shown in Figure 4-26. SMA2 is shown heated and as it recovers, it will rotate the first lever, hinged about point ‘O’, to a new position. SMA1 will be disengaged as lever 1 rotates. For the set up, the required displacement is 5.48mm, linearly.

A prototype of the mechanism (based on the CAD model) was fabricated with two plastic levers assembled, as shown in Figure 4-27. Two extension springs were also installed on the opposite leg of each lever to allow the lever to return to the original position. The left picture of Figure 4-27 showed the initial position of both levers while the right picture showed one of lever actuated.

However, the outcome of the test did not tally with the CAD model. This was because the residual force in the cooling wire was ignored in the model, and this force created a friction that worked against the disengaging lever. For the demonstration, Ø0.5mm SM495 was used. It was observed that the opposing wire was disengaged as the wire moved away from the aluminum marker. However, only a very small improvement of 20% was
achieved in term of actuation time and this was caused by the residual force of the cooling wire that worked against the disengaging lever.

Instead of interlinking the flap actuating SMA to the EDE lever, a separate SMA wire to control the EDE lever can be considered. The SMA for controlling the EDE lever should possess a narrower hysteresis so that it can cool faster than the flap SMA. In this way, larger diameter SMA can be used to control the flap. For example, a 70% improvement (calculated based on the difference in cooling time) in actuation time can be achieved using Ø0.3mm NTC05 to operate the lever, and Ø0.5mm SM495 wires to actuate the flap.

Alternatively, conventional actuation can be considered to work together with the SMA. For example, a differential transformer (or solenoid) can be used to operate the lever to engage/disengage the SMA actuator.

The first point highlighted in Section 4.6 on page 87 can be indirectly solved using the proposal discussed in the above paragraphs. The EDE mechanism, controlled by the SMA with narrow hysteresis or a conventional actuator, can be incorporated to engage/disengage the large diameter flap SMA. However, this concept was not tried out because the required moment to flex the 1.5mm thick shim to the desired angle (5 degrees) is 3555.6Nmm (obtained from Figure 4-5) and this implied the need for multiple SMA (Ø0.5mm) to deflect the thick shim. The values are shown in Table 4-2. The values were calculated in the same way shown in Appendix B3, except the SMA force of 70N was used. It was shown that combinations 1 to 3 were unable to overcome the moment of 3555.6Nmm, only the remaining three combinations that utilized 3 to 4 SMA wires per rib
were suitable. The complexity of controlling the SMA was further increased with the additional of the EDE levers SMA.

Table 4-2: Ø0.5mm SMA Wires Combination - Moment Calculation

<table>
<thead>
<tr>
<th>Wire Combination</th>
<th>Calculated Moment</th>
<th>Achievable Angle for 1.5mm Thick Shim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination 1 (per rib)</td>
<td>1101.8Nmm</td>
<td>Unable to overcome 3555.6Nmm</td>
</tr>
<tr>
<td>1 wire at Pos. C only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination 2 (per rib)</td>
<td>2007.6Nmm</td>
<td>Unable to overcome 3555.6Nmm</td>
</tr>
<tr>
<td>1 wire at Pos. A, 1 wire at Pos. B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination 3 (per rib)</td>
<td>2203.6Nmm</td>
<td>Unable to overcome 3555.6Nmm</td>
</tr>
<tr>
<td>2 wires at Pos. C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination 4 (per rib)</td>
<td>4030.6Nmm</td>
<td>Up to 5.1°</td>
</tr>
<tr>
<td>1 wire at all positions except Pos. D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination 5 (per rib)</td>
<td>4250.4Nmm</td>
<td>Up to 5.9°</td>
</tr>
<tr>
<td>1 wire at all positions except Pos. A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination 6 (per rib)</td>
<td>5156.2Nmm</td>
<td>Up to 6.76°</td>
</tr>
<tr>
<td>1 wire at all positions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.8 Discussion

4.8.1 The shim-based wing prototype

The stiffness of the wing prototype depended on a few factors; the material of the shim, the thickness and length of the shim and the type of external skin used. Rib concept #2 was more flexible because the effective length of the shim was longer when compared with that of concept #1. GF-SR hybrid skin would also increase the wing prototype stiffness if a larger elongation (stretch) was applied.
Chapter 4: The Shim-based Wing Prototype

Throughout the rib/ wing prototype deflection test, some observations were made. During the initial deflection test, the flap movement was observed to be smooth in one direction but jerky in the opposing direction. It looked as if the two wires were exhibiting different characteristics, even though both wires were of the same diameter and length, and the wires were secured at the same positions for both sides (Position C).

Further tests were conducted; this time round each wire was tested individually until the desired angle was achieved. Next, the assembly was again tested with both wires. The result observed was very positive with the flap deflecting at almost equal angles in both directions, and it proved that the earlier observation of wires having different characteristics was incorrect. Instead, the wire installation process was also an important step, care must be exercised to ensure that equal amount of tension was applied to the SMA wires.

The next observation was each time current was passed through the SMA, it would elongate and this phenomenon continued even after many heating-cooling cycles. This was observed for both SM495 and NTC05 wires. The cause of this phenomenon was partly caused by the inaccurate temperature control during the heat treatment and thermo-mechanical training. The temperature was not monitored, especially during thermo-mechanical training, thus the temperature may not have reached the required 200 degrees Celsius. Another possible explanation may be related to the production of these SMA wires. The SMA used in this project were not extruded, instead they were melt-spun. It was reported in [48] that SMA extruded using equal-channel angular extrusion (ECAE, shown in Figure 4-28) possessed improved thermal cyclic stability.
Chapter 4: The Shim-based Wing Prototype

Figure 4-28: ECAE process [49]

The transformation temperatures at stress-free condition decrease while their thermal cyclic stability is improved after ECAE-process due to the grain refinement. ECAE leads to an increase in strength differential between the critical stress to induce martensite and the yield stress of martensite upon grain refinement. Consequently, this brings about a considerable improvement in the thermal cyclic stability of transformation temperatures, thermal hysteresis and transformation strains, and significantly reduces irrecoverable strain levels under constant stresses [48].

Another observation was made during the rib test; by increasing the length of the SMA wire, the angle of deflection could be increased. Increasing the length of SMA wire simply implied increasing the amount of recovery strain, e.g. a 100mm SMA would shrink to 98mm upon heating, while a 150mm SMA would recover to 147mm (assuming a 2% recovery strain). There was a 1mm increment in recovery strain, thus
the angle of deflection would be increased. However, due to the size of the rib, it was not a feasible solution because there was a limitation to the allowable length of wire.

Multiple SMA wires actuation, although would increase the complexity of the actuation design many folds, has a potential of achieving variable flap angle control. Take Wire Combination 6 for example - all positions were installed with a wire. If each wire were controlled individually, then each wire would be able to deflect the rib a small angle.

![Multiple SMA wires actuation](image)

**Figure 4-29: Multiple SMA wires actuation**

The first SMA was heated to deflect angle ‘A’. The angle would be increased to ‘A+B’ when the second SMA was heated. The final angle ‘A+B+C+D’ would be achieved when all four SMA were heated as shown in Figure 4-29.
Chapter 4: The Shim-based Wing Prototype

The complexity of wire installation as well as the micro-controller control program would be drastically increased. Each wire has to be isolated from each other to prevent short circuit, while more sequence and commands were required to control multiple wires. For the two ribs prototype, a total of 16 wires would be required, (8 wires on each rib, 4 to control upward deflection, another 4 to control downward deflection).

4.8.2 The Flexible Skin

One of the biggest challenges faced during the skin fabrication was to bond silicone rubber skin to the glass fibre skin. Various types of adhesives were found unsuitable. Silicone adhesive/sealant was eventually used to bond the silicone rubber. Although the hybrid skin was finally bonded to the glass fibre composite successfully, it was discovered that the 0.5mm thick silicone rubber tends to tear easily when it was stretched. This was because the silicone rubber shrank in the lateral direction when it was stretched longitudinally and the corners of the glass fibre composite would initiate the tear easily. This was overcome by reducing the amount of stretching, in order to reduce the amount of lateral shrinking and the corners of the glass fibre composite were trimmed at the same time.

Overlapping glass fibre composite skin offered lower stiffness when assembled to the wing prototype. Overlapped skin as the name implied has one part of the skin overlapping the moving skin thus creating a small step along the chord-wise direction. To create a true seamless flap design, the gap between the overlapping skins could be over-laid by a thin silicone rubber sheet. However, this would lead to an increased in the overall assembly stiffness of the overlapping skin.
Chapter 4: The Shim-based Wing Prototype

Glass fibre cloth and epoxy (with hardener) must be handled with extreme care, as they were hazardous. Mask and hand gloves must be worn to prevent inhalation and direct contact of glass fibre particles (especially if sanding was done).

4.9 Chapter Summary

The design, fabrication and actuation of the shim-based wing prototype were presented in this chapter. Three rib concepts were firstly described, the sizing and analyses of the metallic shim was presented next. The rib actuation using 0.6mm thick shim was successful, achieving an angle of 7.4°. Next the wing prototype was fabricated and tested; actuation test result was positive with a deflected angle of 5.2° achieved. Larger angle (15°) was also achieved using Ø0.5 SMA. It was conclusive that larger diameter SMA or multiple strands of SMA (small diameter) must be used in order to sustain the hinge moment, and a locking mechanism to bear the aerodynamic load was required if thinner shims were used instead. Two types of flexible skins were experimented, and both were installed and tested on the wing prototype. Lastly, the EDE mechanism prototype was tested and only a 20% improvement in actuation time was achieved. In order to improve the actuation time, SMA with narrow hysteresis or alternatively, differential transformer (or solenoid) must be used to control the lever.
Chapter 5: The Hinge-based Wing Prototype

The shim-based wing prototype, assembled with glass fibre-silicone rubber hybrid skin, was successfully actuated and a deflection angle of 5 degrees was achieved. However, there were contradicting requirements between the aerodynamic loading and actuation rate. Thick shims were required to sustain the aerodynamic load, implying the need for multiple SMA with large diameter to produce a higher force, but this would contradict the other requirement of achieving an actuation rate of 5 degrees per second. In addition, multiple strands of SMA wires required complex controlling and electrical wiring.

In this chapter, the hinge-based wing prototype will be discussed. This version is based on concept #3, and it does not require the metallic shims. A pin joint will be used instead, which will remove the stiffness contributed by the shims. Therefore, the SMA actuator wires are only required to handle the stiffness contributed by the skins and the aerodynamic loads. The contradicting requirements of the shim-based wing prototype will be tackled with this design.

The third concept adopted a pin joint and it seems to have contradicted the objective of this project, which is to design and develop a wing flap to provide smooth camber change for a low speed air vehicle. Although a pin joint is used, the smooth continuous control surfaces can be achieved through the installation of the flexible skins which will cover the discontinuous boundaries of the hinged flap. For this concept, the actuation will be performed with the overlapping skin (Chapter 4, Section 4.5.2).
5.1 The Design based on Concept #3

To reduce the stiffness contributed by the shim (shim-based design), concept #3 was investigated. This concept makes use of a pin joint. Therefore, only frictional force will be experienced at this joint, as opposed to the earlier concept whereby the SMA must also overcome the metallic shim, on top of the skin stiffness and the aerodynamic loads. A mechanism that would lock the flap in position is included. This mechanism is targeted at reducing the power consumed by the SMA when they are kept heated up in order to hold the flap in position in the earlier design. Figure 5-1 showed schematic of the concept.

![Figure 5-1: Conceptual design of hinged flap with locking mechanism](image)

In the neutral position, the locking mechanism will be kept in the locked position by a biasing spring. To actuate, e.g. to deflect downwards, a signal from the micro-controller will trigger a SMA to unlock the mechanism. This SMA will work against the biasing spring to open the jaw. This is followed by a second signal to heat up another SMA for deflection. To keep the flap in the down position, the current applied to the mechanism SMA will be removed, so that the biasing spring will close the jaw.
Chapter 5: The Hinge-based Wing Prototype

5.1.1 Prototype Fabrication of Concept #3

The figure below showed the prototype fabricated using Delrin material. Similar to the first prototype, aluminium rods were also used as spars to span it 150mm across. Flange bearings were used to further reduce the friction at the hinge.

Figure 5-2: Prototype of Concept #3

Figure 5-3: Locking mechanism prototype
Chapter 5: The Hinge-based Wing Prototype

Figure 5-3 showed the prototype of the locking mechanism consisting the locking jaws, lock sprocket and biasing torsion spring. The locking jaws and lock sprocket were wire-cut out of AA6061-T6 aluminium.

Similar to concept #2 flap actuation, the SMA wires were arranged biasing each other, so that ‘forced’ actuation with the bias wire would improve the cooling time (Figure 5-4). The locking mechanism was also activated via SMA wire, working against a torsion spring as shown in Figure 5-4. Four SMA actuators were installed for the flap deflection, two for upward deflection and two for downward deflection. There were 2 locking mechanisms installed, thus requiring two SMA actuators to open the mechanisms.
Chapter 5: The Hinge-based Wing Prototype

5.1.2 Load test of Concept #3 Prototype

The hinged-flap prototype was structurally tested to ensure that the locking mechanism was able to sustain the aerodynamic load. A simple test using weights, placed at the trailing edge of the prototype was performed. In Chapter 4, Section 4.2.1, the maximum hinge moment was calculated to be 629Nmm and in Section 4.2.2, a ten ribs design was proposed. Since the hinge-based wing prototype consisted of two ribs, the required moment is calculated using Equation (18).

\[
Moment_{2\text{Ribs}} = 629 \times \left(\frac{2}{10}\right) = 125.8 \text{Nmm}
\]

(18)

Figure 5-5 below showed the prototype undergoing load test.

![Figure 5-5: Hinged-flap prototype undergoing load test](image)

The figure on the left showed the flap suspending an aluminium plate weighing 160g; this was equivalent to a moment of 157Nmm. The figure on the right showed the flap suspending 300g (moment of 294.3Nmm). No slippage of the jaws was observed. Therefore, the locking mechanism was able to sustain 2.3 times the required load.
5.1.3 Actuation of Concept #3 Prototype

The first actuation test to proof the concept was very successful (performed without the locking mechanism), achieving an angle of 20° using Ø0.2mm Flexinol® 200HT actuator wire as shown in Figure 5-6. Due to reduced stiffness, the small diameter SMA wires were able to deflect the flap to 20° with ease.

Flexinol® 200HT actuator wire, manufactured by Dynalloy Inc. was used to actuate the flap, as well as the locking mechanism. Flexinol® is a trade name for nickel-titanium based shape memory alloy actuator wires and unlike SM495 or NTC05, this SMA is already heat treated and trained. In another word, Flexinol® is a plug and play (or rather cut and install) SMA actuator wire. The stroke of Flexinol® actuator wire is measured as a percentage of the length of wire being used; in this case a conservative 3% was used [50].

Figure 5-6: First actuation test using Ø0.185mm SM495

The hinged-flap prototype, working in conjunction with the locking mechanism is shown in Figure 5-7. The SMA did not elongate during the actuation, thus keeping a constant deflected angle throughout the operation. The actuation test was repeatable, achieving 20
degrees during each test and this confirmed that the SMA (Flexinol®) possessed very stable characteristics as opposed to the in-house trained SM495 and NTC05.

Actuation with load was also attempted; however a single Flexinol® 200HT (for actuating the flap) was only capable of handling 86.35Nmm. This was equivalent to 160g placed 55mm away from the hinge and just 69% of the actual hinge moment required.

A second Flexinol® 200HT actuator wire was introduced, i.e. two wires per rib to enable a flap up (or down), to increase the SMA force in order to handle the hinge moment of 128.5Nmm. The actuation test was conducted again with success, suspending 160g at the trailing edge (equivalent to 157Nmm) and deflecting it 20° (Figure 5-8).

Figure 5-7: Hinged-flap working with locking mechanism
Figure 5-8: Flap actuation with 160g suspended at the trailing edge, with the overlapping skin was installed

5.1.4 Electrical Circuit Design

In order to cater to the additional SMA wires, two more MOSFET were introduced to control the locking mechanism SMA wire actuation. The electrical circuit schematic was shown in Figure 5-9.

The resistors used were as follows; R1-1 to R1-6 were 10kΩ, R2-1 to R2-3 were 100Ω, and R3-1 to R3-3 were also 10kΩ. The MOSFET were protected using a Schottky diode since the SMA wire was a form of inductor. Without the diode, the inductor (SMA) could generate a high voltage and burn out the MOSFET.

P0 signal from BASIC Stamp 2 would trigger MOSFET 5 & 6 to deflect the flap upwards, P1 signal would trigger MOSFET 3 & 4 to deflect the flap downwards, and lastly P2 signal would open the locking mechanism. These signals were triggered manually by means of pushbuttons wired as inputs to the BASIC Stamp. Pushbutton wired to pin 3 of BS2 would send an output signal to perform flap upward deflection, pushbutton wired to pin 4 of BS2 would trigger flap downward deflection. Pushbutton wired to pin 5 of BS2
would move the flap back to neutral position from flap down position, and lastly pushbutton wired to pin 6 would move the flap back to neutral from flap up position. The, electrical wiring of pushbuttons, BS2 input/ output wiring and PBASIC program could be found in Appendix A1 and A3.

![Electrical circuit schematic](image)

**Figure 5-9: Electrical circuit schematic**

Another program, modified from the SMA wire training program, was used for continuous operation of the flap. A latching pushbutton wired to pin 3 would send a signal to open and hold the jaws, followed by a second signal to alternately heat and cool the flap wires.
5.1.5 **DAQ result for Flexinol® 200HT**

Similar tests using Instron tensile machine were performed for this SMA to obtain the heating time versus input current curves, shown in Figure 5-10.

The design load for the flap and locking mechanism was 12N; therefore this load was set as the target to cut off the current. The input current was varied, and the exact length of 180mm (for flap actuation) and 102mm (for locking mechanism) were used. The time for the actuator wire to reach 12N was recorded and plotted as shown in Figure 5-10.

![Figure 5-10: Heating time as a function of input current for flap and locking mechanism actuator wires](image)

To estimate the heating time of the flap and locking mechanism actuator wires, curve fitting of the data was performed to obtain Equations (19) and (20) respectively.

\[
I_{ht}^{Flap} = 0.66515 + \frac{2 \times 2.7828}{\pi} \left( \frac{0.044206}{4(i - 0.45106)^2 + 0.044206^2} \right) \quad (19)
\]

\[
I_{ht}^{LC} = 0.36125 + \frac{2 \times 3.7079}{\pi} \left( \frac{0.076432}{4(i - 0.41575)^2 + 0.076432^2} \right) \quad (20)
\]
Chapter 5: The Hinge-based Wing Prototype

For example, to estimate the heating time for flap actuator wire using an input current of 610mA; it would take approximately 1.4 seconds to reach 12N.

Similar to earlier comparison in Chapter 3, the cooling time was also calculated using the heat balance equation, and since Flexinol® was also a nickel-titanium SMA, the same density and specific heat capacity was assumed. The calculated values were: Rayleigh number of 0.0122, Nusselt number of 0.5688, average convection coefficient of 82.244, and with these values the cooling time was then calculated to be 3.627 seconds. The error was 3.626% when compared to the measured value of 3.5 seconds.

5.1.6 DSC results for Flexinol® 200HT

Figure 5-11 showed the DSC result of the Flexinol® 200HT, the transformation temperatures were shown. This alloy’s hysteresis was 30°C, very similar to SM495. However, this SMA was able to provide a much higher force and stable amounts of memory strain for many cycles [50].

Figure 5-11: DSC result of Flexinol® 200HT
Chapter 5: The Hinge-based Wing Prototype

The maximum force of the SMA was determined using Instron Tensile Machine, and the plot shown in Figure 5-12 indicated that the maximum force that the SMA exerted was 33.5N. This was achieved with an electrical input of 9V, and a current of 1.015A. Attempts to further increase the current resulted in overheating the SMA leading to loss of the shape memory effect.

![Figure 5-12: Maximum force generation by Flexinol® 200HT](image)

5.2 Controllability

Controllability, as defined in Chapter 1, Section 1.2.2, will be governed by the deflection angle of the wing flap and rate of actuation in cycles per second. The wing prototype will be termed highly controllable if large deflection is achieved using SMA with small cross-sectional area, and attaining the required actuation rate shown in Chapter 1, Table 1-2. The targeted deflection angle is 5 degrees or larger and using SMA having diameter of 0.2mm or smaller. Finally, the targeted actuation rate is 5 degrees per second or higher.
Chapter 5: The Hinge-based Wing Prototype

A comparison was made as shown in Table 5-1 on the performance of the two prototypes, and also the different SMA used. It was shown that the hinged prototype offered better SMA wire diameter to cooling time ratio, deflection angle to SMA wire diameter ratio, and deflection angle to number of SMA wires ratio. These ratios indicated that the hinge-based prototype excelled better with respect to actuation rate, deflection angle achieved and simplicity in design (using lesser number of SMA wires).

Table 5-1: Comparison of SMA wires operation

<table>
<thead>
<tr>
<th>Description</th>
<th>Shim Prototype</th>
<th>Hinged Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø0.185 SM495</td>
<td>Ø0.5 SM495</td>
<td>Ø0.2 Flexinol®</td>
</tr>
<tr>
<td>Ø0.2 Flexinol®</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling time (seconds)*</td>
<td>3.388</td>
<td>16.475</td>
</tr>
<tr>
<td>Deflection angle</td>
<td>5.2°</td>
<td>15°</td>
</tr>
<tr>
<td>No. of wires</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Diameter (micron) to Cooling time Ratio</td>
<td>54.60</td>
<td>30.35</td>
</tr>
<tr>
<td>Deflection angle to Diameter Ratio</td>
<td>28.11</td>
<td>30</td>
</tr>
<tr>
<td>Deflection angle to No. of wires Ratio</td>
<td>2.6</td>
<td>15</td>
</tr>
</tbody>
</table>

* The cooling time was measured based on the flap set up.

A second comparison between the shim and hinged prototypes is shown in Table 5-2. The hinged prototype, with Flexinol® 200HT was able to actuate the flap with just two second in between heating; this was equivalent to 0.5Hz actuation frequency as compared to 0.333Hz using SM495 for the shim prototype. In addition, the Flexinol® 200HT only requires 9V, approximately 0.6A compared to 12V-0.8A for Ø0.185mm SM495, and 12V-3A for Ø0.5mm SM495. Lastly Flexinol® 200HT was capable of providing a maximum force of 33.5N, which was approximately 3 times that of Ø0.185mm SM495. Although Ø0.5mm SM495 was able to generate a high force of 70N, due to its very slow cooling it resulted in an actuation frequency of only 0.067Hz. The actuation rate, in this case, was
calculated using the time interval of the BASIC Stamp’s program, set between heating and cooling.

Table 5-2: Controllability Comparison between SM495 and Flexinol

<table>
<thead>
<tr>
<th>Description</th>
<th>Shim Prototype</th>
<th>Hinged Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø0.185 SM495</td>
<td>Ø0.5 SM495</td>
<td>Ø0.2 Flexinol®</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>12V</td>
<td>12V</td>
</tr>
<tr>
<td>Limited Current @</td>
<td>0.8A</td>
<td>3A</td>
</tr>
<tr>
<td>Maximum Force Generated</td>
<td>10.75N</td>
<td>~70N</td>
</tr>
<tr>
<td>Deflection Time (single direction)</td>
<td>1 sec</td>
<td>4 sec</td>
</tr>
<tr>
<td>Interval required between deflection #</td>
<td>3 sec</td>
<td>15 sec</td>
</tr>
<tr>
<td>Calculated Response (only based on cooling interval)</td>
<td>0.333Hz</td>
<td>0.067Hz</td>
</tr>
</tbody>
</table>

@ Resistance contributed by other components, e.g. connecting wires, are not taken into account.
# The intervals between deflections were estimated from the actual deflection of the flap.

Table 5-3: Controllability as a function of input voltage

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Vertical Displacement</th>
<th>Deflection (Degree)</th>
<th>Deflection Time (s)</th>
<th>Rate of Deflection</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.354</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>6.277</td>
<td>20</td>
<td>0.314</td>
<td>2.406</td>
</tr>
<tr>
<td>7.5</td>
<td>33</td>
<td>19.29</td>
<td>4</td>
<td>4.823</td>
<td>3.760</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>21.801</td>
<td>2</td>
<td>10.9</td>
<td>5.414</td>
</tr>
<tr>
<td>12</td>
<td>41</td>
<td>22.293</td>
<td>0.5</td>
<td>44.586</td>
<td>6.626</td>
</tr>
</tbody>
</table>

Note: 4.5V was insufficient to heat up the SMA wire. Deflection time was estimated from video recording.

A third comparison for the controllability of the flap as a function of input voltage was shown in Table 5-3. The rate of deflection and deflection angle would increase as the input voltage was increased from 4.5V to 12V. At 4.5V, the current was insufficient to heat up the SMA for deflection, whereas at 12V, the heating time must be kept short because prolonged heating would totally erase the shape memory effect of the SMA. The actuation
frequency with 12V input was actually 2Hz! However, this was achieved at a risk of the SMA losing its memory effect.

5.3 Discussion

5.3.1 Design Concept

It was verified that deflection angle for flap design based on Concept #2 was affected by stiffness of the prototype assembly, and multiple large diameter SMA wires must be employed to overcome the minimum thickness of 1.5mm (Chapter 4, Table 4-2). Therefore, in order to reduce the stiffness further, Concept #3 was investigated. The initial actuation test showed a promising deflection angle of 20°. With a hinged flap, the stiffness contributed by the shims (earlier design) was removed, therefore allowing smaller diameter SMA wires to achieve large deflection. A locking mechanism was also included into this prototype, which was kept in the locked position by means of a biasing spring. In this way, the power required to hold the flap in desired position would be drastically reduced, as the supply to the SMA would be switched to off by the MOSFET.

The initial operation of the locking mechanism was intermittent. This was due to the tendency of the mechanisms rotating causing uneven opening of the jaws. These rotations lead to interlocking. To rectify the interlocking, a guide (made of Teflon) with threaded holes was fabricated. This guide would slide along an aluminium holder as shown in Figure 5-13, aligned to the centre of the hinge thus allowing even opening of the jaws.
With this concept, the flap of the prototype can be locked in the downward position, and camber morphing is achieved. The objective of the project was accomplished as shown in Figure 5-14.

5.3.2 **Flexinol®200HT**

This commercially available SMA was selected as the actuator because it possessed a more stable characteristics compared with SM495 or NTC05. In the earlier prototype tests whereby SM495 and NTC05 were used, the SMA would continue to elongate even after
many cycles of operation. Therefore, the deflection angle of the flap was affected and this was because the properties of SM495 and NTC05 (trained in house) were not stabilized.

Flexinol® wires were specially processed (the actual type of process was not made known) to have large, stable amounts of memory strain for many cycles [50]. This characteristic was important since the hinged-based wing prototype required a more stringent control in order for the locking mechanism to correctly open and close.

5.3.3 Recovery strain verification

The tension in the flap SMA was calculated in order to verify the assumed recovery strain against the deflected angle. With a load of 160 gram suspended at the end of the flap, a total hinge moment of 157Nmm was generated (Section 5.1.3), which in turn would generate a tension force of 1.15N in each SMA wire. The constrained stress in each wire was calculated to be 36.5MPa (tension force of 1.15N divided by the SMA wire cross-sectional area). It was reported in [50] that for a load of 5000 psi (approximately 35MPa), maintained during cooling, an approximate 3% strain would be obtained.

With 36.5 MPa, the SMA would still be residing in the elastic region, therefore the memory effect would be just the two-way memory effect achieved through thermo-mechanical training. To achieve a larger recovery strain, a higher pre-load should be applied to allow further detwinning to take place. However, a higher pre-load to obtain a larger recovery strain was not required as discussed in the following paragraph.
The linear displacement was measured from the CAD model to verify if a 3% strain was enough to deflect the flap to the desired angle. At neutral position, the anchor point of the SMA at the flap (Pos.1 in Figure 5-15) to the flap hinge was measured to be 24.17mm. The locus of this point with respect to the hinge was plotted, and at 20°, this point would be shifted closer to the hinge measuring 20.27mm (Pos.2 in Figure 5-15). Linearly, this worked out to be a displacement of 3.9mm. Similarly, at 25° this point would be 18.89mm (displacement of 5.28mm) measured from the hinge. Therefore with 3% recovery strain, the 180mm SMA would be shortened to 174.6mm (5.4mm shorter), indicating that it would be able to deflect the flap to at least 25°. However, due to the slot that was cut on the prototype external skin, the deflection angle was limited to 22°.

Figure 5-15: Locus of SMA anchoring point on flap
Chapter 5: The Hinge-based Wing Prototype

The above verification has proved that the recovery strain (3 percent) of the SMA was fully utilized, and thus showed that the applied mode of actuation using SMA in tension agreed with [51], whereby the capacity of the SMA was fully utilized through uniform distribution of the deformation and recovery strain, and using SMA with two-way memory effect.

5.4 Chapter Summary

It was observed that the shim prototype has two limitations; first the deflection angle was hindered by the high stiffness of the assembly, and secondly a locking mechanism was desired to lock the flap in position in order to reduce the power consumption. These limitations were overcome by the hinged prototype described in this chapter, large angle of deflection (20º) was achieved and the flap could be locked in position by the locking jaws of the mechanism. The commercially available Flexinol® actuator wire was used for all actuation due to its stable characteristics and ability to provide a large force. Load test was conducted and it was observed that the flap locking mechanism could sustain a moment of 294.3Nmm. Actuation with load was also performed successfully with two strands of Flexinol® 200HT wires; lifting 160 grams suspended 100mm away. The controllability of the flap between SM495 and Flexinol® was discussed; and it was shown that the hinge-based wing prototype offered the best combination in terms of deflection angle achievable and cooling time. Next, it was also shown that the deflection angle and deflection rate for the hinge-based wing prototype was proportional to the input voltage. Lastly, the recovery strain achieved was verified. It was shown that with the applied constrained stress of 36.5MPa, a 3% recovery strain would be obtained, and this amount of strain was fully utilized to achieve the desired deflection angle of 20°.
Chapter 6: Conclusion

The objective to design and develop a wing flap to enable camber morphing for a low speed air vehicle has been achieved. In fact, two versions of wing prototypes were developed, namely the shim-based wing prototype and the hinge-based wing prototype. Smart actuation using shape memory alloy wires as the actuator was achieved and the deflection angle obtained was 20 degrees. This angle was four times larger than the targeted angle. Compared to some of the designs described in Chapter 2, the developed concept was simpler as it did not require embedding of the SMA. Embedding SMA into the composite skin is a tedious and complex process. Instead of embedding, the developed concept only requires both ends of the SMA to be secured.

To achieve smooth camber change, two types of flexible skins were experimented, namely the glass fibre-silicone rubber hybrid skin and the overlapping glass fibre skin. Both types of flexible skins were feasible and were able to achieve the objective of covering the discontinuous boundaries of the flap.

Extensive work on SMA heat treatments, thermo-mechanical training and measurement were carried out and it was observed that both the heat treatment temperature and thermo-mechanical training cycles affected the transformation temperature of the SMA. The changes in transformation temperatures, resistance and voltage across the various types of SMA wires were measured for SM495, NTC05 and Ni_{25}Ti_{50}Cu_{25}. The results indicated that small diameter SMA would cool faster, and if Ni_{25}Ti_{50}Cu_{25} was available in wire form of Ø0.185mm, very good actuation response would be achieved. This was because
Chapter 6: Conclusion

\(\text{Ni}_{25}\text{Ti}_{50}\text{Cu}_{25}\) possessed very narrow hysteresis, and if available in wire form of small diameter, it was able to produce an actuation rate of 0.784Hz, compared to 0.295Hz achieved by SM495. The measurement has concluded that SMA of small cross-sectional area, coupled with narrow hysteresis would be the most suitable candidate to be applied as an actuator for aerospace application.

The shim-based wing prototype was successfully designed, fabricated and tested. It was installed with 0.6mm thick metallic shim and glass fibre-silicone rubber hybrid skin. The flap of the prototype was deflected 5.2 degrees and 15 degrees using SM495 of Ø0.185mm and Ø0.5mm respectively. The actuation tests were demonstrated without the application of load on the flap, and the actuation rate achieved were 0.333Hz (using Ø0.185mm SM495) and 0.067Hz (using Ø0.5mm SM495). Camber morphing was achieved, making use the SMA to deflect the flap. To sustain the flap in the deflected position, the SMA must be kept heated.

The EDE mechanism prototype was fabricated and tested, although the outcome of the test was not ideal, it has proven that concept possessed the potential of improving the response of the SMA. SMA with narrow hysteresis (or conventional actuators, e.g. solenoid) could be utilized to control the EDE levers instead. In this way, larger diameter SMAs that were able to generate a larger force could be utilized to control the flap.

The development of the hinge-based wing prototype was to tackle the flaw of the shim-based prototype; and that was the contradicting requirement between the shim thickness and actuation rate. Thicker shim was needed in order to sustain the aerodynamic load, but thicker shim required a very large force from the SMA actuator in order to flex. This
eventually led to reduced actuation rate or increased actuation complexity. The hinge-based wing prototype, on the other hand, did not require the SMA actuator to work against a large hinge moment. The SMA wires were only required to overcome the frictional force from the prototype hinge and the aerodynamic load during the deflection. Camber morphing was accomplished by incorporating a locking mechanism to lock the flap in position. The locking mechanism was able to resist a hinge moment of 294.3Nmm, and Flexinol® actuator wires were used for all actuation. Finally, the prototype was successfully tested under load of 157Nmm and achieving 20° deflection angles.

The hinge-based wing prototype, actuated using Flexinol® actuator wires was shown to be highly controllable in Chapter 5, Section 5.2.3. It was actuated using Ø0.2mm Flexinol® actuator and achieving a deflection angle of 20 degrees. An actuation rate of 10 degrees per second was attained. The test results for the hinge-based wing prototype had exceeded the three specified requirements for controllability, and they were deflection angle of 5 degrees or more, using SMA having diameter of 0.2mm or smaller, and achieving an actuation rate 5 degrees per second or better. Therefore, it was concluded that the hinge-based wing prototype possessed better controllability over the shim-based wing prototype.

6.1 Contributions

A novel, yet simple actuation system for a wing flap has been developed. The actuation design is simple, straightforward and modular since these SMA actuators can be easily installed and replaced. No complex embedding of SMA is required.
Multi-segment camber morphing of a wing is made possible with the addition of the locking mechanism for the hinge-based wing prototype. Using the proposed smart actuation, no complex linkages or gears are required. This actually implies that weight contributed by the actuation system is reduced! As an example, a Futaba FUTM300 digital servo-actuator [13] (specified with a torque capacity of 0.63Nm) is compared with the new actuator. The Futaba servo-actuator weighs 49.5 grams, this weight is inclusive of the linkages and actuation horns. On the other hand, the SMA actuator with locking mechanism (40 flap actuating SMA wires, 4 locking mechanism SMA wires and 2 sets of locking mechanism are considered) weigh only a total of 23.8 grams. A tremendous 52% saving in weight was achieved when compared to the mechanical actuator.

Lastly, smooth camber change has been achieved with the development of the flexible skins.

6.2 Recommendations

The current actuation rate of 0.5Hz, achieved using Flexinol® is still not adequate with respect to aerospace application. Therefore, more research should be performed to develop shape memory alloy that can cool rapidly from their austenite finish temperature, in another word, to concentrate on SMA with narrow hysteresis. One good example is \( \text{Ni}_{25}\text{Ti}_{50}\text{Cu}_{25} \). It was suggested in Chapter 3, Section 3.1.3, that \( \text{Ni}_{25}\text{Ti}_{50}\text{Cu}_{25} \) (if available in wire form of Ø0.185mm) should be able to cool within 1.3 seconds from austenite finish temperature to martensite finish temperature, thus achieving a rate of 0.784Hz.

The proposed future work in continuation of the project is a wing capable of multi-segment camber morph, coupled with a morphing wing profile to efficiently cater to
different types of mission requirements. For example; dash mode in offensive mission and slow flying mode for reconnaissance mission.

To achieve the above morphing wing, two objectives must be met. The first objective is to conduct thorough investigation and development on the camber morphing capability of the hinge-based wing prototype. This should be extended across the span of the wing to achieve multi-segment camber morphing using shape memory alloy wires as the actuator. The second objective is to conduct thorough research and investigation and development of a mean to change the shape of the wing profile using shape memory alloy wires.

To achieve the two objectives, the work should begin with the design of wing with a suitable profile, and then integration of the wing with the morphing capability onto a remote controlled, light weight Unmanned Aerial Vehicle. Next, modeling and analyses for structural and dynamic integrity will follow. The integration of the morphing mechanism and SMA wire actuators into the wing can be performed upon concept approval and fabrication. After which, intensive qualifying tests for the smart actuator must be conducted, and this should include functional test with load, reliability test with load, and also test for structural integrity. The interfacing of the SMA controls to the UAV flight computer shall be done next, and finally, thorough hardware-in-the-loop simulation and ground tests will be conducted prior to the actual flight tests.

The possible application of the shim-based concept is landing and take-off flaps of an aircraft. Since landing and take-off flaps are only actuated during landing and taking off, the duration of operation will be shorter. Therefore, the power consumed by the heated
SMA (to keep the flap deflected) will be lower when compared to the continuous operation of the control surfaces throughout the flight after the aircraft took off.

However, thorough investigation and development must also be done to qualify the concept for such utilization. The objective here is to replace the heavy hydraulics currently used by most aircrafts. Similarly, the flap can be designed and tested on a remote control flying platform, and the above-mentioned work listed for the camber-morphing wing can also be adopted.

This concept (landing/ take-off flap) can also be applied onto commercial aircraft, but the qualification will be more stringent since humans are involved (e.g. based on Federal Aviation Association standards). Federal Aviation Regulations for airworthiness contained a series of design requirements: from strength of the structures to the flight requirements (flight qualities and performance), criteria for good design practice, systems, fatigue and flutter, necessary tests, flight and maintenance manual content, and so on [52].

Another possible application of both concepts is for controlling the camber variation of windmill blades used in wind energy harvesting system. The purpose here is to improve the performance of the windmill over a wider range of wind conditions. The camber morphing of windmill blades presented in [23], though feasible, requires the SMA to be embedded, and embedding SMA usually will involve complex fabrication process. In contrast to the embedded SMA design, the SMA actuator will only be required to be secured at both ends onto the blade of the windmill. Simplicity and modularity in design will be achieved since the proposed SMA actuators are easily replaced.
References


References


References


References


Appendix A1

BASIC Stamp modules (Figure A1-1) are micro-controllers (tiny computers) that are designed for use in a wide array of applications. Many projects that require an embedded system with some level of intelligence can use a BASIC Stamp module as the controller. Each BASIC Stamp comes with a BASIC Interpreter chip, internal memory (RAM and EEPROM), a 5-volt regulator, a number of general-purpose I/O pins (TTL-level, 0-5 volts), and a set of built-in commands for math and I/O pin operations. BASIC Stamp modules are capable of running a few thousand instructions per second and are programmed with a simplified, but customized form of the BASIC programming language, called PBASIC. The BASIC Stamp 2 specifications are shown in Table A1-1.

![Figure A1- 1: BASIC Stamp 2](image)

Table A1- 1: Specifications of BASIC Stamp 2

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor Speed</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Program Execution Speed</td>
<td>~4,000 instructions/sec</td>
</tr>
<tr>
<td>RAM Size</td>
<td>32 Bytes (8 I/O, 24 Variables)</td>
</tr>
<tr>
<td>EEPROM (Program) Size</td>
<td>2K Bytes, ~700 instructions</td>
</tr>
<tr>
<td>I/O Pins</td>
<td>16 +2 Dedicated Serial</td>
</tr>
<tr>
<td>Voltage Requirements</td>
<td>5 - 15 volts</td>
</tr>
<tr>
<td>Current Draw @ 5V</td>
<td>3 mA Run / 50 μA Sleep</td>
</tr>
<tr>
<td>PBASIC Commands</td>
<td>42</td>
</tr>
<tr>
<td>Size</td>
<td>1.2&quot;x0.6&quot;x0.4&quot;</td>
</tr>
</tbody>
</table>
PBASIC was specifically developed for the BASIC Stamp as a simple, easy to learn language, and highly optimized for embedded control. It includes many of the instructions featured in other forms of BASIC (GOTO, FOR...NEXT, IF...THEN...ELSE) as well as some specialized instructions (SERIN, PWM, BUTTON, COUNT and DTMFOUT).

**Figure A1- 2: Electrical Wiring to BS2**

- **Pushbutton connection to BASIC Stamp 2**
- **Output from BASIC Stamp 2 to MOSFET**

Figure A1- 2: Electrical Wiring to BS2
HARRIS SEMICONDUCTOR

RFD16N05, RFD16N05SM
16A, 50V, Avalanche Rated N-Channel Enhancement-Mode Power MOSFETs

December 1995

Features
- 16A, 50V
- \( V_{GS} = 0.047 \text{V} \)
- Temperature Compensating SPICE Model
- Peak Current vs Pulse Width Curve
- UIS Rating Curve
- +175°C Operating Temperature

Description
The RFD16N05 and RFD16N05SM N-channel power MOSFETs are manufactured using the MegaFET process. This process which uses feature sizes approaching those of LSI integrated circuits, gives optimum utilization of silicon, resulting in outstanding performance. They were designed for use in applications such as switching regulators, switching converters, motor drivers, and relay drivers. These transistors can be operated directly from integrated circuits.

Packaging

<table>
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<tr>
<th>PART NUMBER</th>
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NOTE: When ordering, use the entire part number. Add the suffix SM to obtain the TO-252AA variant in the tape and reel pack. For RFD16N05SM, add the suffix SM.

Formerly developmental type TA0771.

Absolute Maximum Ratings \( T_C = +25^\circ \text{C} \)

- Drain-Source Voltage \( V_{DS} \)
- Drain-Gate Voltage \( V_{GD} \)
- Gate-Source Voltage \( V_{GS} \)
- Drain Current \( I_D \)
- RMS Continuous \( I_{RMS} \)
- Pulsed Drain Current \( I_{PULS} \)
- Pulsed Avalanche Rating \( E_{AV} \)
- Power Dissipation \( P_D \)

\[
\begin{array}{|l|c|}
\hline
\text{RFD16N05, RFD16N05SM} & \text{UNITS} \\
\hline
V_{DS} & 50 \text{ V} \\
V_{GD} & 50 \text{ V} \\
V_{GS} & 20 \text{ V} \\
I_D & 16 \text{ A} \\
I_{RMS} & \text{Refer to Peak Current Curve} \\
I_{PULS} & \text{Refer to UIS Curve} \\
E_{AV} & \text{Refer to UIS Curve} \\
P_D & 72 \text{ W} \\
P_{T (C1)} & 54 \text{ W/C} \\
T_{J \text{ Max}} & 150^\circ \text{C} \\
T_{J \text{ Min}} & -55 \text{ to } +175^\circ \text{C} \\
T_L & 260 \text{ C} \\
\hline
\end{array}
\]

CAUTION: These devices are sensitive to electrostatic discharge. Users should follow proper ESD handling procedures.

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File Number 2267.3
## Specifications RFD16N05, RFD16N05SM

### Electrical Specifications

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<th>PARAMETER</th>
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<th>UNITS</th>
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<td>( I_D = 350 \mu A, V_{DS} = 0 )</td>
<td>53</td>
<td>-</td>
<td>-</td>
<td>V</td>
</tr>
<tr>
<td>Gate Threshold Voltage</td>
<td>( V_{TH} )</td>
<td>( V_{DS} = V_{GS}, I_D = 200 \mu A )</td>
<td>2</td>
<td>-</td>
<td>4</td>
<td>V</td>
</tr>
<tr>
<td>Zero gate Voltage Drain Current</td>
<td>( I_{SS} )</td>
<td>( V_{GS} = 50 \text{V}, V_{DS} = 0 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>( \mu \text{A} )</td>
</tr>
<tr>
<td>&amp; ( T_J = 25^\circ\text{C} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>( \mu \text{A} )</td>
<td></td>
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</tr>
<tr>
<td>&amp; ( T_J = -100^\circ\text{C} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>( \mu \text{A} )</td>
<td></td>
<td></td>
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<tr>
<td>Gate-Source Leakage Current</td>
<td>( I_{GS} )</td>
<td>( V_{GS} = \pm 20 \text{V} )</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>nA</td>
</tr>
<tr>
<td>On Resistance</td>
<td>( R_{ON} )</td>
<td>( I_D = 16 \text{A}, V_{DS} = 10 \text{V} )</td>
<td>-</td>
<td>-</td>
<td>0.047</td>
<td>g</td>
</tr>
<tr>
<td>Turn-On Time</td>
<td>( t_{ON} )</td>
<td>( V_{GS} = 2 \text{V}, I_D = 6 \text{A}, R_L = 3 \text{k}\Omega, V_{GS} = 12 \text{V}, R_{DS} = 2 \text{k}\Omega )</td>
<td>-</td>
<td>-</td>
<td>65</td>
<td>ms</td>
</tr>
<tr>
<td>Turn-On Delay Time</td>
<td>( t_{(ON)} )</td>
<td>( I_D = 1 \text{A} )</td>
<td>-</td>
<td>11</td>
<td>-</td>
<td>ns</td>
</tr>
<tr>
<td>Rise Time</td>
<td>( t_r )</td>
<td>-</td>
<td>30</td>
<td>-</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Turn-Off Delay Time</td>
<td>( t_{(OFF)} )</td>
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<td>55</td>
<td>-</td>
<td>ns</td>
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<tr>
<td>Fall Time</td>
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<td>ns</td>
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<td>Turn-Off Time</td>
<td>( t_{(OFF)} )</td>
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<td>ns</td>
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<tr>
<td>Total Gate Charge</td>
<td>( Q_{G(T)} )</td>
<td>( V_{DS} = 0 \text{V} ) to ( 20 \text{V} )</td>
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<td>-</td>
<td>80</td>
<td>( \mu \text{C} )</td>
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<td>Gate Charge at 10V</td>
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<td>Threshold Gate Charge</td>
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<td>( \mu \text{C} )</td>
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<td>( V_{DS} = 2 \text{V}, V_{GS} = 0 \text{V}, f = 1 \text{MHz} )</td>
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<td>( \text{pF} )</td>
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<td>Output Capacitance</td>
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<td>( \text{pF} )</td>
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<td>Reverse Transfer Capacitance</td>
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<td>-</td>
<td>( \text{pF} )</td>
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<td>Thermal Resistance Junction-to-Case</td>
<td>( R_{JJC} )</td>
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<td>( ^\circ\text{C/W} )</td>
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<td>Thermal Resistance Junction-to-Amount</td>
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<td>( T = 25^\circ\text{C} ) and ( T = 25^\circ\text{C} )</td>
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<td>( ^\circ\text{C/W} )</td>
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### Source-Drain Diode Specifications

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<tr>
<th>PARAMETER</th>
<th>SYMBOL</th>
<th>TEST CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
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<td>Forward Voltage</td>
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<td>V</td>
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<td>Reverse Recovery Time</td>
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<td>-</td>
<td>125</td>
<td>ns</td>
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</tbody>
</table>
Appendix A2

**Theoretical Calculation of Cooling Time**

\[ \rho := 6450 \quad \text{Density of wire} \]

\[ C_p := 836 \quad \text{Specific heat of wire} \]

\[ \phi := \frac{0.185}{1000} \quad \text{Diameter of wire} \]

\[ \phi = 1.85 \times 10^{-4} \quad l := 0.3 \quad \text{length of wire} \]

\[ \text{vol} := \frac{\pi \phi^2 l}{4} \quad \text{vol. of wire} \]

\[ \text{area} := \pi \phi l \quad \text{Surface area of wire} \]

**Calculation of heat convection coefficient for diameter 0.185mm NTC05**

Rayleigh number

\[ Ra := \frac{9.81 \cdot 0.0031422 \cdot (345.5 - 314) \cdot \phi^3 \cdot 0.7105}{(17.5903 \cdot 10^{-6})^2} \]

\[ Ra = 0.014 \]

Nusselt number

\[ Nu := \left[ 0.6 + \frac{1}{0.387 \cdot Ra^6} \right]^{2/8} \left[ \frac{9}{1 + \left( \frac{0.559}{0.7105} \right)^{16}} \right]^{27/28} \]

\[ Nu = 0.574 \]

Average convection coefficient

\[ h := \frac{Nu \cdot 0.02754}{\phi} \]

\[ h = 85.522 \]

For \( 10^{-5} < Ra_L < 10^{12} \)

\[ Nu_D = \frac{h_D D}{k} = \left[ 0.6 + \frac{0.387 \cdot Ra_D^{1/6}}{1 + \left( \frac{0.559}{Pr} \right)^{9/16}} \right]^{8/27} \]

**Calculate Cooling Time from A1 to MF**

\[ Q_{out} := \rho \cdot V \cdot C_p \frac{dT}{dt} \]

\[ t := \frac{-\rho \cdot C_p \cdot \text{vol} \cdot \ln \left( \frac{314 - 293}{345.5 - 293} \right)}{h \cdot \text{area}} \]

\[ t = 2.672 \quad \text{experimental time} \]

\[ t_{exp1} = 2.91665 \]

\[ \text{error1} := \left( \frac{1 - t_{exp1}}{t_{exp1}} \right) \cdot 100 \]

\[ \text{error1} = -8.389 \]
Appendix A2

Calculation of heat convection coefficient for diameter 0.3mm NTC05

\[ \phi_1 := \frac{0.3}{1000} \]

Rayleigh number

\[ Ra_1 := \frac{9.81 \cdot 0.0031214 \cdot (350 - 315) \cdot \phi_1^3 \cdot 0.7104}{(17.8136 \cdot 10^{-6})^2} \]

for dia 0.3mm NTC05
\[ A_f = 350 \quad M_f = 315 \]

\[ Ra_1 = 0.065 \]

Nuelt number

\[ Nu_1 := 0.6 + \frac{1}{0.387 \cdot Ra_1} \left( \frac{0.559}{0.7104} \right)^{27} \]

\[ Nu_1 = 0.646 \]

Average convection coefficient

\[ h_1 := \frac{Nu_1 \cdot 0.027695}{\phi_1} \]

\[ h_1 = 59.618 \]

Calculate Cooling Time from \( A_f \) to \( M_f \)

\[ Q_{out} := \rho \cdot V \cdot C_p \cdot \frac{d(T)}{dt} \]
\[ vol_1 := \frac{\pi \cdot \phi_1^2}{4} \]
\[ area_1 := \pi \cdot \phi_1 \cdot 1 \]

\[ t_1 := \left( \frac{-\rho \cdot C_p \cdot vol_1}{h_1 \cdot area_1} \right) \ln \left( \frac{315 - 293}{350 - 293} \right) \]

\[ t_1 = 6.458 \]
\[ t_{exp2} = 6.085 \]

\[ error_2 := \left( \frac{t_1 - t_{exp2}}{t_{exp2}} \right) \cdot 100 \]

\[ error_2 = 6.129 \]
Appendix A2

Calculation of heat convection coefficient for diameter 0.185mm SM495

Rayleigh number

\[
Ra2 := \frac{9.81 \cdot 0.0031399 \cdot (346 - 303) \cdot \phi^3 \cdot 0.7105}{(17.6151 \cdot 10^{-6})^2}
\]

for dia 0.185mm SM495

\[A\phi = 346 \cdot M = 303\]

\[Ra2 = 0.019\]

Nusselt number

\[
Nu2 := 0.6 + \left[ \frac{1}{6} - \frac{0.387 - Ra2}{8} \right]^2 \left[ 1 + \left( \frac{0.559}{0.7105} \right)^{27} \right]
\]

\[Nu2 = 0.587\]

Average convection coefficient

\[
h2 := \frac{Nu2 \cdot 0.02756}{\phi}
\]

\[h2 = 87.471\]

Calculate Cooling Time from At to Mf

\[-Q_{out} := \rho \cdot V \cdot C_p \cdot \frac{dT}{dt} \]

\[t2 := \left( \frac{-\rho \cdot C_p \cdot V \cdot \text{vol}}{h2 \cdot \text{area}} \right) \ln \left( \frac{303 - 293}{346 - 293} \right)\]

\[t2 = 4.755 \quad t_{\exp} := 3.3875\]

error3 := \left( \frac{t2 - t_{\exp}}{t_{\exp}} \right) \cdot 100

\[error3 = 40.363\]
Appendix A2

Calculation of heat convection coefficient for 2mm x 0.06mm NiTiCu25

\[
\text{vol4} = \left( \frac{2}{1000} \right) \left( \frac{0.06}{1000} \right) 0.3 \quad \text{area4} = \left( \frac{2.06}{1000} \right) 0.3
\]

\[
\text{char_length} = \frac{\text{vol4}}{\text{area4}}
\]

Reynolds number

\[
\text{Re4} = \frac{9.31 \times 0.0031 \times 61 (344 - 336.5) \text{ char_length}^2 \times 0.7106}{(17.3159 \times 10^{-6})^2}
\]

\[
\text{Re4} = 2.475 \times 10^{-4}
\]

Nusselt number

\[
\text{Nu4} = 0.678 \times \text{Re4}^{0.25} \left( \frac{0.7106}{0.9552 + 0.7106} \right)^{0.25}
\]

\[
\text{Nu4} = 0.069
\]

for 2mm x 0.06mm NiTiCu25

\[A1 = 344 \quad \text{MT} = 326.5\]

Average convection coefficient

\[
\text{h4} = \frac{\text{Nu4} \times 0.027483}{\text{char_length}}
\]

\[
\text{h4} = 52.443
\]

Calculate Cooling Time from A1 to MT

\[-Q_{out} = -p \cdot V \cdot C_p \frac{dT}{dt}\]

\[
\text{t4} = \left( \frac{-p \cdot C_p \cdot \text{vol4}}{\text{h4} \cdot \text{area4}} \right) \ln \left( \frac{326.5 - 29.3}{344 - 29.3} \right)
\]

\[
t4 = 4.069 \quad t_{\exp4} = 3.7125
\]

\[
\text{error4} = \left( \frac{t4 - t_{\exp4}}{t_{\exp4}} \right) \times 100
\]

\[
\text{error4} = 9.606
\]
Appendix A2

**Calculation of heat convection coefficient for diameter 0.185mm NiTiCu25**

Rayleigh number

\[
Ra_3 := \frac{9.81 \cdot 0.0031491 \cdot (344 - 326.5) \cdot \phi^2 \cdot 0.7106}{(17.5159 \cdot 10^{-6})^2}
\]

for dia 0.185mm NiTiCu25

\[
Af = 344 \text{ Mf} = 326.5
\]

\[
Ra_3 = 7.928 \times 10^{-3}
\]

Nusselt number

\[
Nu_3 := \left[ 0.6 + \frac{1}{6} \frac{0.387 \cdot Ra_3}{8} \left[ 1 + \left( \frac{0.559}{0.7106} \right)^{27} \right]^{\frac{9}{16}} \right]^2
\]

\[
Nu_3 = 0.553
\]

Average convection coefficient

\[
h_3 := \frac{Nu_3 \cdot 0.027485}{\phi}
\]

\[
h_3 = 82.121
\]

**Calculate Cooling Time from Af to Mf**

\[
-Q_{out} := \rho \cdot V \cdot \dot{C}_p \cdot \frac{dT}{dt}
\]

\[
t_3 := \left( \frac{-\rho \cdot \dot{C}_p \cdot \text{vol}}{h_3 \cdot \text{area}} \right) \ln \left( \frac{326.5 - 293}{344 - 293} \right)
\]

\[
t_3 = 1.276
\]
PBASIC Programs for SMA Wire Training and Actuation

PBASIC Program for Training

'Training Program for SMA wire

' {STAMP BS2}
' {PBASIC 2.5}

counter VAR Word

Reset:
DO WHILE IN3<1 'wait for button press
LOOP
counter = 0 'reset counter to 0
DEBUG "Start Training", CR
PAUSE 3000

Heating:
IF IN3 = 0 THEN STOP
DEBUG "Heating", CR
HIGH 1 'heating start
PAUSE 5000 'hold for 5sec
DEBUG "Cooling", CR
LOW 1 'cooling start
PAUSE 8000 'hold for 8sec

counter = counter + 1
DEBUG ? counter
IF counter < 80 THEN heating

PBASIC Program for Actuation

'Actuation Program for SMA wire

' {STAMP BS2}
' {PBASIC 2.5}

counter VAR Word
timer1 VAR Word
timer2 VAR Word

Reset:
DO WHILE IN3<1 'wait for button press
LOOP
counter = 0                   'reset counter to 0
DEBUG "Start Training", CR
PAUSE 3000

Heating:
IF IN3 = 0 THEN STOP
DEBUG "Heating sma1", CR
HIGH 1                       'heating sma1 start
PAUSE 3000                   'hold for 3sec
FOR timer1 = 1 TO 30       'set timer1 to count up to 10
PULSOUT 1, 500
PAUSE 500
NEXT
LOW 1                         'current supply cut for sma1
PAUSE 8000                 'pause 1 sec
DEBUG "Heating sma2", CR
HIGH 0                        'heating sma2 start
PAUSE 3000                   'hold for 3sec
FOR timer2 = 1 TO 30         'set timer1 to count up to 10
PULSOUT 0, 500
PAUSE 500
NEXT
LOW 0                         'current supply cut for sma2
PAUSE 5000                  'pause 5sec

counter = counter + 1
DEBUG ? counter
IF counter < 100 THEN heating
PBASIC Program for Hinged Flap with Locking Mechanism Actuation
Training Program for SMA wire

' {$STAMP BS2}
' {$PBASIC 2.5}

Restart:
DEBUG "Press Desired PB", CR
IF (IN3 = 1) THEN
  GOSUB FlapUp
ENDIF
IF (IN4 = 1) THEN
  GOSUB FlapDown
ENDIF
IF IN5 = 1 THEN
  GOSUB FlapDwnNeutral
ENDIF
IF IN6 = 1 THEN
  GOSUB FlapUpNeutral
ENDIF

FlapDwnNeutral:
IF (IN5 = 0) THEN Restart
DEBUG "Go back to neutral position from Flap Down position", CR
HIGH 0  'SMA_L heating start to unlock jaws
PAUSE 2000 'hold for 3sec (to check on timing)
HIGH 1  'SMA_Fup heating to actuate flap upwards to neutral
PAUSE 1700
LOW 0   'SMA_L cooled to lock jaws
PAUSE 500
LOW 1   'SMA_Fup cooling start
GOTO Restart

FlapUpNeutral:
IF (IN6 = 0) THEN Restart
DEBUG "Go back to neutral position from Flap Up position", CR
HIGH 1   'SMA_Fup heated to prevent flap from dropping upon jaws opening
PAUSE 500
HIGH 0   'SMA_L heating start to unlock jaws
PAUSE 5000 'Pause 5sec to keep jaws open
LOW 0    'Cut off supply to SMA_Fup
LOW 1    'SMA_L cooled to lock jaws
PAUSE 500
GOTO Restart

FlapUp:
IF (IN3 = 0) THEN Restart
DEBUG "Unlock", CR
Appendix A3

HIGH 0                      'SMA_L heating start to unlock jaws
DEBUG "Flap up", CR
HIGH 1                      'SMA_Fup heating to actuate flap upwards
PAUSE 10000                 'SMA_Fup heated 10sec to deflect up
DEBUG "Locked", CR
LOW 0                       'SMA_L cooled to lock jaws
PAUSE 2000
LOW 1                       'SMA_Fup cooling start
GOTO Restart

FlapDown:
IF (IN4 = 0) THEN Restart
DEBUG "Unlock", CR
HIGH 1                      'SMA_Fup heated to prevent flap from dropping upon jaws open
PAUSE 500
HIGH 0                      'SMA_L heating start to unlock jaws
LOW 1                       'Cut off supply to SMA_Fup
PAUSE 2500                  'hold for 0.65sec for jaws to clear sprocket
DEBUG "Flap down", CR
HIGH 2                      'SMA_Fdw heating to actuate flap downwards
PAUSE 10000                 'Pause 10sec to deflect down
DEBUG "Locked", CR
LOW 0                       'SMA_L cooled to lock jaws
PAUSE 500
LOW 2                       'SMA_Fdw cooling start
GOTO Restart
Appendix A4

Other DSC Results

Figure A4-1: DSC Result of SM495 (as-received)

Figure A4-2: DSC Result of SM495 after Annealing at 580°C for 20 minutes
National Instruments CompactDAQ

National Instruments CompactDAQ hardware provides the plug-and-play simplicity of USB to sensor and electrical measurements. This system combined the ease of use and low cost of a data logger with performance and flexibility of modular instrumentation. NI CompactDAQ delivers fast and accurate measurements in a small, simple, and affordable system. With the LabVIEW SignalExpress, NI CompactDAQ can be easily used to log data for simple experiments or to develop a fully automated test or control system. The modular design can measure up to 256 channels of electrical, physical, mechanical, or acoustical signals in a single system. In addition, per-module analog-to-digital converters and individually isolated modules ensure fast, accurate and safe measurements. Plug-in modules NI 9211 and NI 9219 (Figure A5-1), with 4-channels each, were used for thermocouples and resistance/voltage measurements respectively.

NI CompactDAQ was set-up because it was a modular (flexibility); connectors/ signal conditioning/ and DAQ were available in a single package and easy PC connectivity with high speed USB. The software, LabVIEW SignalExpress was interactive, measurement software for quickly acquiring, analyzing, and presenting data from hundreds of data acquisition devices and instruments, with no programming required. It allows the user to acquire, log, and export data to ASCII or have it displayed in Microsoft Excel with ease. In addition, it was capable of inline analysis functions, data logging alarms and events, documentation view, multiple data logging files in a single project and other more advanced data logging operations.
Figure A5-1: NI CompactDAQ with NI 9211 & 9219
Cooling Time Determination Using Instron 5548 Tensile Machine

Figure A6-1: Ø0.185mm SM495 Cool Time using Instron 5548 (500 - 650mA)

Figure A6-2: Ø0.185mm SM495 Cool Time using Instron 5548 (700 - 850mA)
Figure A6-3: Ø0.185mm NTC05 Cool Time using Instron 5548 (800 - 950mA)

Figure A6-4: Ø0.185mm NTC05 Cool Time using Instron 5548 (1.25 - 1.4A)
Figure A6-5: Ø0.3mm NTC05 Cool Time using Instron 5548 (1 - 1.15A)

Figure A6-6: Ø0.3mm NTC05 Cool Time using Instron 5548 (1.2 - 1.35A)
Figure A6-7: 2mm x 0.06mm Ni$_{25}$Ti$_{50}$Cu$_{25}$ Cool Time using Instron 5548 (0.9 - 1.2A)

Figure A6-8: 2mm x 0.06mm Ni$_{25}$Ti$_{50}$Cu$_{25}$ Cool Time using Instron 5548 (1.3 - 1.6A)
Figure A6-9: 180mm Flexinol®200HT for flap actuation (399mA applied)

Figure A6-10: 180mm Flexinol®200HT for flap actuation (479mA applied)
Figure A6-11: 180mm Flexinol®200HT for flap actuation (533mA applied)

Figure A6-12: 180mm Flexinol®200HT for flap actuation (575mA applied)
Figure A6-13: 180mm Flexinol®200HT for flap actuation (666mA applied)

Figure A6-14: 180mm Flexinol®200HT for flap actuation (712mA applied)
Appendix A6

Figure A6-15: 180mm Flexinol®200HT for flap actuation (766mA applied)

Figure A6-16: 180mm Flexinol®200HT for flap actuation (799mA applied)
Appendix A6

Figure A6-17: 180mm Flexinol®200HT for flap actuation (1.065A applied)

Figure A6-18: 102mm Flexinol®200HT for locking mechanism actuation (415mA applied)
Figure A6-19: 102mm Flexinol®200HT for locking mechanism actuation

(508mA applied)

Figure A6-20: 102mm Flexinol®200HT for locking mechanism actuation

(565mA applied)
Appendix A6

Figure A6-21: 102mm Flexinol®200HT for locking mechanism actuation

(622mA applied)

Figure A6-22: 102mm Flexinol®200HT for locking mechanism actuation

(679mA applied)
Figure A6-23: 102mm Flexinol®200HT for locking mechanism actuation

(846mA applied)

Figure A6-24: 102mm Flexinol®200HT for locking mechanism actuation

(905mA applied)
Figure A6-25: 102mm Flexinol®200HT for locking mechanism actuation

(1.015A applied)
### Appendix B1

**SPRING STEEL SHIM**  
**MATERIAL:** (Made In Japan)  
**Grade:** JIS G3311 SK-5  
**Finish:** White Polish with Sheared Edges  
**HARDENED AND TEMPERED**  
**Hardness:** HV 415-450

#### Hardness conversion table

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<th>Tensile Strength N/mm² (kgf/mm²)</th>
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</table>

(SAE J 417)
**DELRIN®**

POLYOXY-METHYLENE (COPOLYMER)

**STOCK COLOR: BLACK/ WHITE (NATURAL)**

**GENERAL PROPERTIES**

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Ref</th>
<th>Typical Values</th>
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<tbody>
<tr>
<td><strong>PHYSICAL</strong></td>
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<tr>
<td>Specific Gravity (g/cm³)</td>
<td>D792</td>
<td>1.41</td>
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<tr>
<td>Water Absorption, 24 hrs (%)</td>
<td>D570</td>
<td>0.24</td>
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<td><strong>MECHANICAL</strong></td>
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<tr>
<td>Tensile Strength (psi)</td>
<td>D638</td>
<td>11,000</td>
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<tr>
<td>Tensile Modulus (psi)</td>
<td>D638</td>
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<td>Tensile Elongation at Break (%)</td>
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<td>Compressive Strength (psi)</td>
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<td>Hardness, Rockwell</td>
<td>D785</td>
<td>M89/R122</td>
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<tr>
<td>IZOD Notched Impact (ft-lb/in)</td>
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<tr>
<td><strong>THERMAL</strong></td>
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<td>Coeff. Of Thermal Expansion (x10⁻⁵ in/in/°F)</td>
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<tr>
<td>Heat Deflection Temp (°F/°C) @ 264 psi</td>
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<td>250/121</td>
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<td>Melting Temp (°F/°C)</td>
<td>D3418</td>
<td>347/175</td>
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<td>Max Operating Temp (°F/°C)</td>
<td>-</td>
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<tr>
<td>Thermal Conductivity (BTU-in/ft²-hr-°F)</td>
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<td>Flammability Rating</td>
<td>UL94</td>
<td>HB</td>
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<tr>
<td><strong>ELECTRICAL</strong></td>
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<tr>
<td>Dielectric Strength (V/mil) short time, 1/8&quot; thk</td>
<td>D149</td>
<td>450</td>
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<tr>
<td>Dielectric Constant at 1MHz</td>
<td>D150</td>
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<td>Dissipation Factor at 1MHz</td>
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<tr>
<td>Volume Resistivity (ohm-cm) at 50% RH</td>
<td>D257</td>
<td>10¹⁵</td>
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</tbody>
</table>

**ADVANTAGES:**
- High Strength, Stiffness
- Dimensional Stability
- Very Low Moisture Absorption
- Good Wear and Abrasion Resistance
- Easy to Machine

**APPLICATIONS INCLUDE:**
- Industrial Assembly
- Fixture

**PRODUCT CAPABILITIES:**

**STOCK SHAPES**
- Rod: 6mm-200mm
- Sheet: 5mm-100mm

**DELRIN® is the registered trademark of DuPont**
SMA Wires Combination - Force Calculation

Combination 1 (1 wire at position C)

\[ F_{2y_{\text{total}}} = 2 \times (10 \sin 9) \]
\[ F_{2y_{\text{total}}} = 3.128N \]

\[ M_{2_{\text{total}}} = 2 \times (10 \times 7.87) \]
\[ M_{2_{\text{total}}} = 157.4Nmm \]

Combination 2 (1 wire at position A, 1 wire at position C)

\[ F_{1y_{\text{total}}} = 2 \times (10 \sin 24.03) + 2 \times (10 \sin 9) \]
\[ F_{1y_{\text{total}}} = 11.268N \]

\[ M_{1_{\text{total}}} = 2 \times (10 \times 6.47) + 2 \times (10 \times 7.87) \]
\[ M_{1_{\text{total}}} = 286.8Nmm \]

Combination 3 (2 wires at position C)

\[ F_{3y_{\text{total}}} = 2 \times F_{2y_{\text{total}}} = 2 \times 3.128 = 6.256N \]
\[ M_{3_{\text{total}}} = 2 \times M_{2_{\text{total}}} = 2 \times 157.4 = 314.8Nmm \]

Combination 4 (1 wire at each position except position D)

\[ F_{6y_{\text{total}}} = F_{4y_{\text{total}}} - (2 \times 10 \sin 6.82) \]
\[ F_{6y_{\text{total}}} = 16.927N \]

\[ M_{6_{\text{total}}} = M_{4_{\text{total}}} - (2 \times 10 \times 8.04) \]
\[ M_{6_{\text{total}}} = 575.8Nmm \]
Appendix B3

Combination 5 (1 wire at each position except position A)

\[ \begin{align*}
F_{5y_{total}} &= F_{4y_{total}} - (2 \times 10 \sin 24.03) \\
F_{5y_{total}} &= 11.158N
\end{align*} \]

\[ \begin{align*}
M_{5_{total}} &= M_{4_{total}} - (2 \times 10 \times 6.47) \\
M_{5_{total}} &= 607.2Nmm
\end{align*} \]

Combination 6 (1 wire at each position)

\[ \begin{align*}
F_{4y_{total}} &= 2 \times (10 \sin 24.03) + 2 \times (10 \sin 16.42) + 2 \times (10 \sin 9) + 2 \times (10 \sin 6.82) \\
F_{4y_{total}} &= 19.302N
\end{align*} \]

\[ \begin{align*}
M_{4_{total}} &= 2 \times [(10 \times 6.47) + (10 \times 14.45) + (10 \times 7.87) + (10 \times 8.04)] \\
M_{4_{total}} &= 736.6Nmm
\end{align*} \]