Design and testing of shape memory alloy actuation mechanism for flapping wing micro unmanned aerial vehicles

N F Kamaruzaman and E J Abdullah*
Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

*ermira@upm.edu.my

Abstract. Shape memory alloy (SMA) actuator offers great solution for aerospace applications with low weight being its most attractive feature. A SMA actuation mechanism for the flapping micro unmanned aerial vehicle (MAV) is proposed in this study, where SMA material is the primary system that provides the flapping motion to the wings. Based on several established design criteria, a design prototype has been fabricated to validate the design. As a proof of concept, an experiment is performed using an electrical circuit to power the SMA actuator to evaluate the flapping angle. During testing, several problems have been observed and their solutions for future development are proposed. Based on the experiment, the average recorded flapping wing angle is 14.33° for upward deflection and 12.12° for downward deflection. This meets the required design criteria and objective set forth for this design. The results prove the feasibility of employing SMA actuators in flapping wing MAV.

1. Introduction
Unmanned aerial vehicles (UAVs) can be defined as a “device used or intended to be used for flight in the air that has no on-board pilot” [1]. Current generations of UAVs “can be as small as an insect or as large as a charter flight” [2]. They are typically launched from a road or a small vehicle, and are large enough to house cameras, sensors or other information-gathering equipment. The recent researches on UAVs are looking into the design and control of the tilt-rotor UAVs, which is a hybrid aircraft that can perform high-speed flights like fixed-wing aircraft and can also operate in hover conditions on top of performing vertical take-off and landing (VTOL) like helicopters and quadrotors. Most of them have been equipped with fixed or rotary wings, and switch between helicopter and fixed-wing aircraft flight modes by tilting their rotors. UAVs have the advantages over manned vehicles since the functions and operations can be implemented at a much lower cost, faster and safer.

SMA wire actuator is a stepping stone towards further development of flapping wing technology. SMA materials are metallic alloys that undergo martensitic transformation when they are subjected to applied thermo-mechanical loads. SMA can be activated by external heating (i.e. ambient temperature) or electrical heating (i.e. Joule heating with electrical current). SMAs are very attractive for actuation purposes because of their large excitation forces and displacements. With their characteristics of high power-to-weight ratio, large recovery strain and low driving voltage, SMA actuators have been widely used in a variety of applications including aircraft wing control, robotic gripper, active endoscope and automotive mirror actuator.
Micro Air Vehicle (MAV) is a miniature aircraft with maximum wing span of 15 cm (i.e. about 6 inches), as defined by the Defense Advanced Research Programs Agency (DARPA) [3]. This physical size limitation puts MAVs at least an order of magnitude smaller than any operational UAVs. MAVs that are developed by the University of Florida, in particular, vary in wingspan from 4 to 6 inches and can carry a payload up to 15 g [4]. There are three main categories of MAVs: fixed wing, rotary wing and flapping wing. The use of MAVs for military operations has also become more common today. A new trend in the MAV community is to take inspirations from flying insects or birds to achieve better flying capabilities [5]. For instance, a 50 g mechanical insect known as Entomopter is designed using Reciprocating Chemical Muscle to actuate four wings for its flapping flight. The wings are created by using stereolithography and fused deposition modelling techniques, and produce a flapping frequency of 70 Hz [6]. The study of flexible flapping-wing Micro Air Vehicles (FMAs) has fascinated many researchers because of their aerodynamic benefits, particularly in low Reynolds number and small size [7]. Owing to their advantages of small size, low velocity, high agility and manoeuvrability, micro or small ornithopters are being potentially considered for applications in rescue missions, remote sensing, and spy and reconnaissance operations in small or closed media. The flapping flyers, inspired from the biological flappers, have a flexible wing structure. They use the root cyclic driving input (i.e. cranking moment) and a passive bending and twisting motion due to flexibility in both span-wise and chord-wise directions. The flapping of the flexible wings is characterized by the simultaneous generation of lift and thrust forces. Moreover, characteristics of loads acting on them, including aerodynamic, inertia and internal elastic loads, can vary substantially over one flapping cycle [8]. Therefore, understanding the aerodynamic, structural and flight dynamic attributes of flapping is necessary to design the high-performance and robust FMAs [9]. There are few variables to consider when conducting researches regarding tandem wing configuration such as gap distance between the paired wings, phase angle of each wing, aerodynamic performance [10], and endurance of the wings subjected to harsh conditions. To produce high performance membrane wing structures, aerodynamic-featured wing profile needs to be inherent in the design of the membrane wing.

An effective mechanical flapping system is important to produce the sufficient lift and thrust forces required for flying a flapping wing MAV. When concerning a smaller size ornithopter [11] or insects with ornithopter-like flapping wing kinematics like butterfly, a smaller and more compact mechanical flapping system configuration than a four-bar crank rocker mechanism is required. Therefore, a slider crank is introduced [12]. The extensive usage of piezoelectric materials is limitless due to their robust deformation. A flexible piezoelectric actuator is mounted underneath the wings of an ornithopter-type MAV to gain camber control during flapping flight and when an electrical field is fed, the actuator will deform and control the camber of the wings with its deformation [13].

2. Shape Memory Alloy
SMAs are a unique group of materials that have the capability to recover from large deformation well beyond the normal elastic strain limit of metals. This behaviour is associated with the thermoelastic martensitic phase transformation from the parent phase austenite (A) to the phase martensite (M). This property renders the materials the capability to produce mechanical work output without requiring any complex mechanical design. Furthermore, the deformation recovery might occur spontaneously upon the unloading of the stress that causes the deformation (referred to as the pseudoelasticity) or delayed from the time of deformation until the material is heated at a later stage at a different location (referred to as the shape memory effect). Owing to these special features, SMAs have been used in a wide range of innovative designs and smart structures like actuator sensors, medical devices, miniature devices, damping absorbers and fibre reinforced composite structures [14]. SMAs have also been proposed in robotics as an alternative to the conventional electric, hydraulic and pneumatic motors because of the increasing need to develop smaller and lighter robots. Indeed, one of the advantages of this technology is the lighter actuator with bigger power/weight ratio, therefore making SMAs a valid alternative to conventional actuators [15].
SMA has aroused continuous attention mainly because of its two distinctive characteristics: shape memory effect (SME) and pseudoelasticity (SE). Shape memory effect refers to the behaviour of alloy that undergoes a phase transition under the influence of temperature, pressure, mechanical effect and other factors. Self-adapting wing structure of shape memory alloy refers to the base material, sensing element, driving element and electronic control system that are all integrated together. According to external changing environment and their own situation, they can adapt based on self-diagnosis of the structure adjustment. If the aircraft wings have self-adapting deformation ability, they can improve the performance of the system to a great extent, especially in improving the radius of gyration, increasing endurance, increasing the load and improving the obvious advantages of maximum speed [16]. Several research has been carried out in related fields such as structural design of stealth fighter using SMA to drive the folding wing. Recently, Chengdu aircraft group has also introduced manufacturing process of memory alloy technology [17].

It can be said that a big potential can be seen for shape memory actuator in aerospace industry but its application has yet to be widely spread presently. Boeing has also embarked in a project to employ the SMA technology for morphing aircraft with component and system level optimization at multiple flight conditions [18]. A particular attention is paid to flapping wing using this SMA since they are the least developed so far and their characteristics are not widely known. It can be seen that SMA actuator can replace the motor and significantly reduce the system's weight. Due to limited previous study on the feasibility of employing SMA on flapping wing, this work is carried out to explore its potential by designing a flapping wing MAV actuating mechanism using SMA actuator “muscles” to actuate the wing.

3. Methodology
The aim of the experiments is to understand the behaviour of the selected two different types of SMA samples. The result is then used to select and determine the suitable spring type or wire type of SMA to be applied in the proposed flapping wings, and to identify the design parameters. The two types of SMA sample (i.e. spring and wire) as shown in Table 1 are used as the guidelines for comparison with the properties from the manufacturer. Behaviour of the SMA with regards to voltage activation power supply, time-to-contract and few other parameters are recorded for further analysis. Figure 1 shows the experiment setup.

| Table 1: Material properties of SMA samples |
|-----------------|-----------------|-----------------|
| **Type**       | **Spring**      | **Wire**        |
| **Material**   | Nickel Titanium (NiTi) | Nickel Titanium (NiTi) |
| **Resistance** | Not stated      | 12.2 Ohm/meter  |
| **Length**     | 2 cm            | 35 cm           |
| **Maximum Deformation** | 15 cm | Not stated |
| **Activation Temperature** | 45-50 °C | 70-90 °C |
| **Number of Windings (Spring)** | 21 | N/A |
| **Outer Diameter (Wire)** | 0.75 mm | 0.31 mm |
| **Outer Diameter (Winding)** | 6.5 mm | N/A |

The results of the experiment are tabulated in Table 2, which indicate that the SMA wire began to activate and contracted when 1.5V and 0.19A current power is supplied. The maximum recorded SMA
wire contraction recorded is 2cm at supplied power of 3.5V and average 0.51A. Further voltage and current increment is found to give no additional contraction to the SMA wire. On the other hand, the SMA spring is fully activated and contracted as much as 3.7cm at supplied power of 7V and average 2.23A. The SMA spring sample began to activate and contracted when 2V and 0.28A current power is supplied. Based on these results, wire type SMA has given the fastest contraction as compared to the spring type SMA. For the cooling process, wire type SMA has also given the fastest time to cool as compared to the spring type SMA. It is decided to convert the SMA wire into a spring and it has been performing better than the manufactured SMA spring.

The schematic diagram is shown in Figure 2 illustrates the use of four SMA wire-spring to provide the force required to flap the wing. When the power supply connected to the circuit on top of the wing is turned ON, the wire reacts and the wing flaps upwards. When the top circuit is switched OFF while the bottom circuit is switched ON, the wing flaps downwards. From the conducted experiments, it is observed that the SMA wire-spring has taken a short time to cool. This can be contributed to the faster subsequent movements.

The fabrication of the flapping wing is depicted in Figure 3. The body of the wing is made from bamboo while the wing is made from aluminium plate. The prototype is tested using DC power supply to verify the functionality of the flapping mechanism. Figure 4 shows the setup for the testing. The experiment is conducted continuously with increasing power using the same sample. The displacement of wing tip is measured manually in order to determine the angle of deflection.

| SMA Type | Activation Voltage (Volts) | Maximum Compression (cm) |
|----------|---------------------------|--------------------------|
| Spring   | 7.0                       | 3.7                      |
| Wire     | 3.5                       | 2.0                      |

Electrical activation is calculated using Equation 1 to Equation 3 for the resistance, voltage and the power, respectively, where \( \rho \) is the SMA resistivity, \( L \) is the free length of element and \( A \) is the cross sectional area.

\[
R = \frac{\rho L}{A} \quad (1)
\]

\[
V = IR \quad (2)
\]

\[
W = I^2R \quad (3)
\]
The activation requirements for the wire and spring type SMA are used in the design selection. The design of the actuator has been determined by investigating the selected materials of both types using experimental analysis result. The angle of deflection can be calculated by Equation 4.

\[ \tan^{-1} \theta = \frac{L_2 - L_1}{\frac{1}{2} \text{wing span}} \]  

4. Results and Discussion

The final design chosen for this study is as shown in Figure 5 and Figure 6. The engineering drawing is done using CATIA V5 software. During the assembly design, the operation of the mechanism can be tested to verify that it functions as expected. From the results of SMA behaviour experiments, the prototype testing is conducted to see the movement of the wings using wire-spring type SMA. The data obtained is tabulated in Table 3 when the wing is flapped upwards and Table 4 when it is flapped downwards. From the data, the flapping angle is observed to generally increase as the supplied power is increased.

Figure 5: CATIA drawing of selected design

Figure 6: Detail description of the selected design
Table 3: Data obtained with power (upward flapping)

| Power (W) | Deflection (deg °) |
|-----------|-------------------|
| 0         | 0                 |
| 0.048     | 0                 |
| 0.195     | 0.212             |
| 0.473     | 0.424             |
| 0.853     | 0.637             |
| 1.363     | 0.849             |
| 1.940     | 1.379             |
| 2.696     | 1.803             |
| 3.637     | 2.650             |
| 4.699     | 3.812             |
| 5.777     | 6.336             |
| 7.326     | 8.623             |
| 8.740     | 14.334            |

Table 4: Data obtained with power (downward flapping)

| Power (W) | Deflection (deg °) |
|-----------|-------------------|
| 0         | 0                 |
| 0.041     | 0                 |
| 0.177     | 0.424             |
| 0.415     | 0.743             |
| 0.754     | 1.061             |
| 1.223     | 1.697             |
| 1.780     | 2.438             |
| 2.472     | 3.391             |
| 3.319     | 5.074             |
| 4.223     | 6.754             |
| 5.221     | 8.010             |
| 7.326     | 9.871             |
| 8.740     | 12.122            |

The rate of change of the flapping angle is nonlinear as illustrated in Figure 7 and Figure 8. The flapping of the wing becomes bigger and the flapping angle rises faster when the power is higher. It is also observed that the upward flapping produces a bigger deflection in comparison to the downward flapping angle of the wing. This is believed to be due to prototype fabrication that affects the flapping angle.

Figure 7: Power versus flapping (upwards)

Figure 8: Power versus flapping (downwards)

5. Conclusions

This paper presents the design of smart actuator involving two types of SMA samples. The concept is then expanded to identify the best actuator concept to be imposed in this design, as the SMA spring and SMA wire chosen to be the main element. SMA wires are able to contract upon electrical heating and they have been used as artificial biceps that allow the wing to contract. From the results, it can be concluded that the design of actuator replacement and its integration into the flapping wing MAV is successful. Heat is applied to the wire using an input electric current. The cooling of the system is through convection with the surrounding area. In order to improve the proposed design in this paper, further studies have to be carried out like exploration of cooling techniques and investigation of wing morphing by means of SMA. With regards to the former, development of a viable means to increase the cooling rate of a SMA wire would prove advantageous with respect to the attainable stroke length and range of motion at increasing speed. The design requirement for designing the flapping wing such as amplitude and expected wing displacement also needs to be defined.
Acknowledgement
The authors would like to acknowledge that the research findings presented in this paper is funded by Research University Grant Scheme (RUGS): UPM/700-2/1/GPB/2017/9530800 from Universiti Putra Malaysia.

References
[1] Bolkcom C 2004 Homeland Security: Unmanned Aerial Vehicles and Border Surveillance CRS Report for Congress
[2] McCormack E D 2008 Use of Small Unmanned Aircraft by the Washington State Department of Transportation Washington State Transportation Center
[3] Ifiu P G, Ettinger S, Jenkins D A and Martinez L 2001 SAMPLE Journal 37 7-13
[4] Abdulrahim M, Garcia H and Lind R 2005 Journal of Aircraft 42 131-7
[5] Markose S, Patange S, Raja S and Salice P 2014 International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering 3 444-51
[6] Michelson R C and Naqvi M A 2003 RTO-AVT von Karman Institute for Fluid Dynamics Lecture Series
[7] Shyy W, Aono H, Chimakurthi S K, Trizila P, Kang C K, Cesnik C E S and Liu H 2010 Prog Aerosp Sci 46 284–327
[8] Lewin G C and Hajhariri H 2003 J. Fluid Mech 492 339–62
[9] Sane S P and Dickinson M H 2002 J. Exp. 205 1087–96
[10] Broering T and Lian Y 2012 Acta Mech Sin 28 1557–71
[11] Lee J S, Kim J K, Han J H and Ellington C P 2012 J Bion Eng 9 18–28
[12] Sun M and Xiong Y 2005 J Exp Biol 208 447–59
[13] Lee J S, Han J H and Kim D K 2011 8th International Conference on Ubiquitous Robots and Ambient Intelligence
[14] Bashir S, Meng S Q, Mahmud A S and Wu Z 2017 Journal of Material and Design 124 225-37
[15] Nespoli A, Besseghini S, Pittaccio S, Villa E and Viscuso S 2010 Sensors and Actuators A: Physical 158 149–60
[16] Quan D and Hai X 2015 Procedia Engineering 99 1241-46
[17] Chinese Patent No. 201080034831
[18] Calkins F T, Mabe J H and Ruggeri R T 2008 ASME 2008 Conference on Smart Materials