Shape memory alloy actuation effect on subsonic static aeroelastic deformation of composite cantilever plate

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Abstract. Shape memory alloy (SMA) is one of the smart materials that have unique properties and used recently in several aerospace applications. SMAs are metallic alloys that can recover permanent strains when they are heated above a certain temperature. In this study, the effects of SMA actuation on the composite plate under subsonic aeroelastic conditions are examined. The wind tunnel test is carried out for two configurations of a cantilever shape memory alloy composite plate with a single SMA wire fixed eccentrically. Strain gage data for both bending and torsional strain are recorded and demonstrated during the aeroelastic test for active and non-active SMA wire in two locations. The cyclic actuation of the SMA wire embedded inside the composite plate is also investigated during the aeroelastic test. The results show reduction in both bending and torsional strain of the composite plate after activation of the SMA wire during the wind tunnel test.

1. Introduction
In the last few decades, smart structures become an interesting new area of research in aerospace engineering fields. Many researchers’ work on adaptive structures embedded with smart materials and investigate their ability to reduce the aeroelastic difficulties and improve the wing performance. Static aeroelasticity is one of these difficulties where the aerodynamics load induced by steady flow interacts with elastic force of the wing structure. This phenomenon has a great impact on the performance, structure load distribution and the stability of the aircraft [1, 2]. The reason behind using an adaptive structure is because this type of structure has the ability to modify the material characteristics or its shape by using actuators [3], such as piezoelectric or shape memory alloys (SMAs) that are available in the industry.

Shape memory alloy is one of the commercialized smart materials and it has unique characteristics as actuator where it can change its physical geometry and mechanical properties, and has self-healing capacity [4, 5]. This type of material could provide new control methods with less complexity and small weight actuators. SMAs mainly undergo two different phases: martensite phase (M) that occurs in low temperature and the stiffness is low, and austenite phase (A) that occurs in high temperature and the stiffness is higher than that in martensite. In terms of exhibition, SMA can demonstrate two unique properties: pseudoelasticity and shape memory effect [5]. SMAs in the form of wires or thin films can be embedded in a host composite material to form a smart composite structure. The potential benefits of embedded actuators are the ability of controlling external shape, changing stiffness and providing vibration control of the composite.
There are two methods widely used to fabricate composite plate embedded with shape memory alloy. The first one is direct embedded where the SMA wires are separately clamped in jig during the fabrication of composite plate and then cured [6, 7]. On the other hand, the second method is by using sleeves embedded with dummy wire and replace with SMA wired after the composite has cured [8, 9]. It is difficult to fabricate a structure with direct embedded SMA with high reliability as the electrical resistive heating required for actuator activation may cause cracks in the structure or de-bonding of SMA actuator from the structure. One of the reasons that the second method by sleeve tubes is used in this test is because it is easy to replace the SMA wire if there is a need, which is it not applicable in the first method.

In control point of view, SMA wire can be used passively or actively to control static or dynamic properties of the composite structure. Passive method is mainly used to increase the strength of the composite. However, in active method, SMA is activated to change the stiffness, shape or vibration frequency of the structure. Active property tuning (APT) and active strain energy tuning (ASET) are two ways to actively control the static or dynamic properties of the structure. For APT, the SMA wires are not pre-strained and don’t generated recovery forces. Meanwhile, the second technique is ASET where SMA are pre-strained and the recovery stress is generated during activation [10].

In terms of commercial exploitation, nickel-titanium alloys and copper-based alloys are the two most successful and each displays different properties. Nickel-titanium alloys are known to have a greater shape memory strain and thermally stable, with excellent corrosion resistance and higher ductility. On the other hand, copper-base alloys are much less expensive, and they can be melted and extruded in air easily, plus have a wide range of potential transformation temperatures. Characteristics of both alloy systems must be considered for any particular application. Thus far, nickel-titanium has proven to be the most flexible and beneficial in engineering applications [26]. Hence, nickel-titanium alloy is exploited in this current work.

Static aeroelastic is one branch of aeroelasticity where the forces involved are only elastic and aerodynamic forces. These forces can be lead to difficulties that should be taken into consideration in design process of wing such as on lift distribution, divergence and control system reversal phenomena. The analysis of the spanwise aeroelastic lift distribution is important mainly in two ways: to fulfill the requirements of performance analysis that requires the knowledge of the total moment and force on the aircraft as a function of altitude and flight condition, and to ensure the integrity of the aircraft structure for specific flight condition such that the stress analysis can be conducted [1]. The bending and torsion moment on the wing can be found and the maximum stress generally will be located on the wing root. Several research works have been carried out on static aeroelasticity. For example, Bea Jae-Sung et al. [11] studied the aeroelastic deformation and conducted static aeroelastic analysis of a variable-span morphing wing. The results show increased bending moment at the root of the wing due to an increase wingspan, hence larger bending stiffness is required in the wing structure. For low aspect ratio wing, a study conducted by Standford et al. [12] investigated the static aeroelasticity of micro air vehicle wing, which is presented with an experimental and numerical analysis. Also studies on both static and limit cycle oscillation aeroelastic analyses for high aspect ratio wing model have been done by Tang and Dowell [13] where theoretical modal was developed and compared with experimental test. On the other hand, there are earlier studies on using smart material for static aeroelastic. Weisshaar and Ehlers [14] investigated the effect of piezoelectric layer attached on laminated wing structure and observed an increase in divergence speed.

Adaptive structures are defined as structures that can modify their material properties and shape. They can be also formed either by passive, active or intelligent smart structures [3], and become a new technique to design the wing structure. Nam et al. [16] studied the effects of SMA spar design in composite wing on the aeroelastic performance improvement. On dynamic aeroelasticity, literature studies like Barzegari et al. [15] studied numerically the limit cycle oscillation amplitude of a wing embedded with pre-strained SMA wire and illustrated the significant improvement in the in-plane load effect of the SMA wire on aeroelastic behaviors. Additionally, SMA is used in applications where it is required to control the structure's vibration and natural frequencies. Some of these studies include that
of Ostachowicz et al. [17], in which they presented a detailed finite element analysis of SMA fibers embedded inside a composite plate and the results showed the great influence of the SMA on natural frequency. They concluded that there is a great potential effectiveness to control the vibration of the composite structures by embedding SMA actuator under applied heat. Lau et al. [18] evaluated the natural frequencies using analytical model of composite beam embedded with SMA wires clamped at both ends while Zhang et al. [19] investigated both theoretically and experimentally the vibration characteristics of composite plate embedded with SMA in different arrangement. They reported that in the high temperate phase transformation (austenite phase) of the SMA wire, the natural frequency is higher than that in the lower phase. There are also other studies on dynamic properties of composite plate such as John and Harir [20] where they mounted the SMA wire over the plate.

Other applications of the shape memory alloy in aerospace include using it to control the shape of wing or airfoil. Baz et al. [21] introduced the mathematical model on shape control of NITINOL strips embedded inside composite beam and the obtained results showed possibility of controlling the shape of the composite beam without compromising their structural stiffness or frequencies. Icardi and Ferrero [22] studied the feasibility of using SMA torsion actuator in adaptive wing with flexible ribs and skin to change the airfoil shape and they presented in finite element method. There are several studies on using the SMA actuator in improving the aerodynamic performance on of the wing [23, 24]. Some studies also remarked on control of the shape memory alloy by constructing control system. One of these studies is by Abdullah et al.[25] whereby a Proportional–Integral–Derivative (PID) control system for SMA actuator wire that was attached on the top of composite plate was developed and the results showed an effective response.

In this present work, the focus is on using active embedded shape memory alloy to reduce the stress that is generated on the top plate during aeroelastic effect by measuring the strain. When aerodynamic loads start to twist the plate tip, the angle of attack is consequently increased which generates more lift until it reaches the equilibrium condition. That additional lift adds more moments and torsion forces on the plate root, which leads to more stress on the structure and eventually decrease the life span of the wing. Thus experimental tests on two different configurations of SMA cantilever plates are conducted. SMA wires inside the composite plates are activated by DC power supply during the test and the effect of the eccentric force that is generated during the activation of SMA wire is observed and recorded through the strain gage reading for both bending and torsional strains.

2. Material and methodology

2.1. Material

The actuators used in this experiment are Flexinol® 70C® (Dynalloy, Inc), SMA wire ready-to-use pre-strained 5-8 % and the pull force of single wire is 1250 g. The wire properties are listed in Table 1. For the composite plate in the experiment, four layers of E-glass fiber (with dimension 35 x 25 cm) are used as reinforcement since the fiber glass has poor electric conductivity compared to carbon fiber or Kevlar. For the matrix, EpoxAmite®100 with 103 Hardener is used. For the sleeve, silicone tubes Nexsilz (Tomo Heater & Rubber Sdn. Bhd.) with inner and outer diameters of 1.2 mm and 2.2 mm, respectively, are used.

2.2. Fabrication

To accommodate the alignment of the sleeves embedded within the composite layers, a rectangular jig is used with one side is fixed for holding one end of the sleeve and the other side is adjustable for tightening the other end of the sleeve. Vacuum infusion technique is used to fabricate the composite plate to improve the consolidation of the structure. Firstly, a smooth waxed surface was prepared and laid two layer of E-glass. The silicone tubes were then embedded with dummy wires in each tube and aligned in straight lines, and the two remaining layers of the fiber glass were then placed on top. The resin feed lines, peel ply and vacuum bag were installed. The resin was prepared where the epoxy and
the hardener were added with a ratio of 1:3 and infused inside the bag with pressure at 100 bars and then cured at room temperature.

| Table 1. Flexinol wire properties |
|-----------------------------------|
| **Parameter** | **Value** |
| Diameter (mm) | 0.30 |
| Density (g/cm³) | 6.45 |
| Specific Heat (cal/g/°C) | 0.20 |
| Melting Point (°C) | 1300 |
| Latent Heat of Transformation (cal/g) | 5.78 |
| Thermal Conductivity (W/cm/°C) | 0.18 |
| Thermal Expansion Coefficient (°C⁻¹) |  |
| Martensite | 6.6 x 10⁻⁶ |
| Austenite | 11.0 x 10⁻⁶ |
| Poisson Ratio | 0.33 |
| Linear Resistance (Ω/m) | 12.2 |
| Electrical Resistivity (approx.) (µΩ.cm) |  |
| Martensite | 80 |
| Austenite | 100 |

Two specimens with a dimension of 285 mm x 40 mm are cut by vertical band saw after de-mold. The composite plate with one embedded silicone tube for each specimen is as shown in Figure 1. The dummy wire was removed and replaced carefully with single Flexinol® SMA wire that was free to move inside the sleeve during activation. The numbers in the specimen “SE05” and “SE15” indicate the distance of the SMA wire from the leading edge (L.E.), which was 5 and 15 mm, respectively. Two metal c-shape barriers with 1 mm hole in the middle were clipped at both ends of each specimen and then crimped the end of the SMA wire. Since the structure was a flat plate, it is assumed that the location of the aerodynamic center at which the aerodynamic lift acted on it was located in the quarter of the chord measured for the leading edge and the elastic axes were at the center mid of the chord. Therefore, the SMA was located in two locations in between the leading edge and elastic axes to study the effect of the force that countered the aerodynamic force and moments on the plate.

![Figure 1. Schematic diagram of two composite plates embedded with SMA](image-url)
2.3. Method
The research was carried out with two main types of test. First test, the SMA wire inside the cantilever composite plate was activated with absence of airspeed, which means there was no aerodynamic load acting on the plate and both bending and torsional strain gages were observed. This test was done to analyze the effect of the contraction force that was generated when the SMA was activated on the cantilever plates. In the second test, static aeroelastic test was conducted in which the airspeed inside the wind tunnel was increased up to 30 m/s and the strain gages responses were recorded, initially with non-active SMA and later with the SMA wire embedded to the plate was activated and de-activated, and these were repeated three times during the operated wind speed to examine the cyclic effect. In the beginning, correlation between the SMA wire temperature and the voltage that was generated from DC power supply was made to set the amount of electricity to activate the shape memory alloy wire.

2. Experiment setup

2.1. Temperature measurement
Temperature measurements of SMA wire with 285 mm were carried out to correlate the temperature with the voltage. SMA wire was hanged in test stand and a dead weight of 5 N was connected at the end of it as depicted in Figure 2. Thermocouple (K type) was attached in the middle of the SMA wire to measure the temperature during heating by electric power. In this test, DC power supply (GW Instek GPS-3030D) was used and the data acquisition was executed via NI DAQ-9211 module associated with LabVIEW. Isolated tape was used in contact surface during the test.

2.2. Wind tunnel test
In this present study, the experiment was conducted in open circuit subsonic wind tunnel at Aerospace Lab, Aerospace Engineering Dept., Universiti Putra Malaysia. The cross section of the wind tunnel is (1 x 1 m) and its maximum operating airspeed is 40 m/s with variable driving system. Side-wall test rig was mounted on the side wall of the wind tunnel [26], which consists of three main parts: rigid frame that supports all the parts, rotating desk that allows the plate to rotate with different angles of attack and a clamped system to fix the plate in the frame.

Cantilever plates with effective length of 250 mm (aspect ratio= 6.25) were fixed first to thick steel arm as shown in Figure 3, which was used for holding the plates and placed it to the middle stream of the wind tunnel to avoid the boundary layer of the wall . The arm and plates were mounted straight (un-swept) in the side-wall test rig with angle of attack (α =1°). Strain gauges (KYOWA Tri-axial KFRP-5-120-D22) were located and attached on the top surface of the plate at 100 mm from fixed end. The data for both bending and torsional strain were monitored by using NI DAQ associated with LabVIEW. Two vinyl-coated electric wires connected to DC power supply (GW Instek GPS-3030D) were attached to both end of shape memory wire. The experiment set-up is shown schematically in Figure 4. The wind tunnel speed was monitored by digital manometer instrument (Testo 510) and Figure 5 shows the composite plate embedded with SMA wire inside the wind tunnel.

Figure 2. Temperature measurement of Flexional SMA wire setup

Figure 3. Experiment setup
3. Results and discussion

3.1. Correlation of temperature with voltage
For this test, the relation between the temperature and the voltage of the SMA wire is shown and the results are plotted in Figure 6. Starting with room temperature where the SMA undergoes in martensite phase, the temperature data are recoded with a voltage interval of 0.5V up to 4V. It can be observed from the data that the temperature increases gradually with voltage. The recommended temperature from the Flexinol manufacture to operate the SMA wire is at 70 °C. As a result, electrical DC power was activated with absence of airspeed. In the beginning, all the strain gauges were calibrated and started from zero strain. SMA activation wire generated force on the plates increases the bending strain gradually up to 1.5 V and subsequently increases rapidly after that until it reached 3V (this voltage correlated with ~ 69 °C). The bending strain of plate “SE05” recorded 10.8 micron-strain at 3V but it was higher for plate “SE15” at the same voltage, which reached up to 16.6 micron-strain. On the other hand, torsion strain data shows negative strain during increasing the voltage and plate “SE15” recorded the highest torsional strain of -37.0 micro-strain. Other observation was during the cooling down of the SMA wire by de-activation, the strain gauges did not reach to their initial status that was recorded before activating the SMA wire at zero volt. The positive bending and torsion signs are shown in Figure 8.

3.2. Activating plate with absence of airspeed
In this test, the SMA wire inside the cantilever plates (SE05 &SE15) was activated with absence of airspeed or dynamic pressure. The outcomes of the test are plotted in Figure 7. In the beginning, all the strain gauges were calibrated and started from zero strain. SMA activation wire generated force on the plates increases the bending strain gradually up to 1.5 V and subsequently increases rapidly after that until it reached 3V (this voltage correlated with ~ 69 °C). The bending strain of plate “SE05” recorded 10.8 micron-strain at 3V but it was higher for plate “SE15” at the same voltage, which reached up to 16.6 micron-strain. On the other hand, torsion strain data shows negative strain during increasing the voltage and plate “SE15” recorded the highest torsional strain of -37.0 micro-strain. Other observation was during the cooling down of the SMA wire by de-activation, the strain gauges did not reach to their initial status that was recorded before activating the SMA wire at zero volt. The positive bending and torsion signs are shown in Figure 8.
3.3. Static aeroelastic deformation test
In this aeroelastic test, the airspeed inside the wind tunnel was operated at 30 m/s and the plate started to deform under the aerodynamic forces (Figure 8). The variation of strain gauge readings before and after activating the SMA wire inside the cantilever composite plates is illustrated in Figure 9 and Figure 10. The first observation during examining the data shows that each configuration of the plates “SE05” and “SE15” has higher strain in bending in terms of magnitude than torsion strain. Moreover, the initial bending strain gauges of non-active SMA at 30 m/s of wind speed recorded negative values for both composite plates embedded with SMA. The bending strain reading for plate “SE05” and “SE15” was -162.10 and -106.14 micro-strain, respectively. On the other hand, torsion strain gauge readings for the both showed positive values, the first plate “SE05” scored 102.05 micro-strain while the other remaining plates “SE15” scored 35.31 micro-strain. The initial strain gauge of both plates in this test is not the same and this may be due to the vortex generated on the tip of the plates because the clip that held the SMA wire varied from one plate to another.

![Figure 8. Plate bending and twist sketch due to aerodynamic forces with non-active SMA.](image)

![Figure 9. Bending strain gauges at airspeed 30 m/s for plates: (a) SE05, (b) SE15.](image)

![Figure 10. Torsional strain gauges at airspeed 30 m/s for plates: (a) SE05, (b) SE15.](image)
After that, the SMA wire inside the composite plates was activated up to 3V while the wind speed was operating at same speed. The eccentric force started to generate at the activation temperature of the SMA. For plate SE05, the results showed that the bending strain was reduced from its initial status before activation by 5.82% where the strain reading reach up to -152.7 micro-strain. Meanwhile, for plate SE15, there was also reduction of around 3.23%. For torsional effect, the activation of the SMA wire generated a considerable force and started to reduce the strain readings for both plates. Plate “SE15” scored the highest strain reduction by around 10%.

The experimental values of the bending and torsional strain during SMA cyclic activation wire at airspeed of 30 m/s are tabulated in Table 2. The cyclic data are normalized by dividing the strain gauge readings of each active plate (SE05 and SE15) with their initial non-active SMA at the same condition of wind speed, which is plotted in Figure 11. The cycle number (0) in x-axis in the figure indicates the SMA wire is non-active. $\varepsilon_i$ indicates the strain gauge at each cycle number $i = 1, 2$ and $3$ are active whereas $\varepsilon_0$ represents initial reading of strain gauge during non-active SMA and $k$ are for plate SE05 and SE15.

In the cyclic effect test, the first plate SE05 bending strain was reduced at the first cycle by 5.8% as mentioned earlier. However, in the second and third cycle, the reduction reached around 5.46% and 4.35%, respectively. On the other hand, in the torsional strain, the reduction was fluctuating with 5.91% at the first cycle and then declined to 4.66% at the second cycle. The reduction then increased at the third cycle and reached 11.2%. For the second plate SE15, both bending and torsional strain readings scored the highest reduction at the second cycle with 10.92% and 25.1%, respectively, and then the reduction decreased around to 7% in the bending strain and 18% in the torsional strain.

| Sample | Strain | Bending | Torsional |
|--------|--------|---------|-----------|
|        |        | Not Active | Active cycle | Not Active | Active cycle |
|        |        | (1) | (2) | (3) | (1) | (2) | (3) |
| SE05   | Micro Normalize | -162.10 | 1.0 | -152.66 | 0.94 | -153.25 | 0.95 | -155.05 | 0.96 | 102.05 | 1.0 | 96.01 | 0.94 | 97.29 | 0.95 | 90.62 | 0.89 |
| SE15   | Micro Normalize | -106.14 | 1.0 | -102.71 | 0.97 | -94.54 | 0.89 | -98.93 | 0.93 | 35.31 | 1.0 | 31.92 | 0.90 | 26.48 | 0.75 | 28.95 | 0.82 |

*Normalize = \[\text{Active SMA cycle}_{k}(i) / \text{Not Active SMA}_{k}\] ; where $i$ is cycle 1, 2 and 3 & $k$ is plate SE05 and SE15

![Figure 11](image-url). Normalized SMA activation cyclic effect on: (a) bending (b) torsion strain gauges at airspeed 30 m/s

4. Conclusion
Two configurations of composite plate embedded with SMA wire: SE05 and SE15 were fabricated. Experimental evaluation on strain gauges of active cantilever plate was conducted in two cases: first without aerodynamic load where the airspeed was zero and second with airspeed at 30 m/s. During the
second case, the cyclic effect of the SMA actuator on the structure was also studied. In the first case, it is found that by activating the pre-strained SMA wire inside the composite plate, both bending and torsional strain readings are changed due to actuation of the shape memory alloy wire that produced large recovery force that was generated during the heating of the SMA wire by electricity. From the results, positive bending strain values are observed in both plates, which indicates that tension stress was generated on the top surface of the composite plate. On the other hand, torsional strain readings were negative and that shows that twist occurred during the activation of the SMA wire and change started to take place when the voltage was around 1.5-2V.

In the static aeroelastic deformation test, when the airspeed inside the wind tunnel reached up to 30 m/s, the two non-active cantilever composite plates started to deform due to aerodynamic forces that acted on the wing. With relatively large aspect ratio, each plate started to deform due to the aeroelastic effect that could be observed from the strain gauge readings. In addition, the plates had bending strain greater than torsional and this is expected since the aspect ratio is 6.25. However, during the activation of the embedded SMA wire, the strain gauge readings (bending and torsional) for both plates were reduced. The active SMA, besides increase in the overall stiffness (from austenite phase to martensite phase), it also produced recovery force that operated as eccentric force that started to counter balance the aerodynamics moment and forces generated during the wind tunnel test.

On the cyclic effect, it can be observed that the effect of SMA force was reducing in subsequent cycles, except in the plate SE05 where the torsional strain in the third cycle was higher than the second cycle. However, for the remaining cases, the effect was reducing. This result highlights the limitation in the number of times that SMA wire can be used in one operation set before it was trained or reset it again. Furthermore, there was a small accumulated residual strain to the plate, which it can be seen on the first test in absence of airspeed where the strain gauge did not reach to zero strain when the SMA was de-activated. This condition may lead to the discrepancy in trend between the cycles.

In the end, reduction on the strain gage during static aeroelastic deformation test and considerable effects of the embedded active SMA have been shown for both configuration plates. The results show that both configurations have near effect change in bending and torsional strain gauge for each plate separately in the first and the last activation. Further studies are required to develop full understanding of the SMA effect on composite plates with low angles of attack by aligning the SMA wire in different location or configuration that could lead to a significant role in adaptive wing design in the future.

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