Vibration Tuned Fiber-Glass Composite by using Shape Memory Alloys

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Abstract: Research on improving structural performance using shape memory alloy (SMA) has been stepping up recently and drawn great interest from both industry and academic. A current research effort extends the utilization of SMA for the invention of smart composite structures due to its striking advantages, e.g. shape memory effect, pseudo-elasticity and high damping capability. In this paper, the application of SMA to control structure oscillation is presented where the influence of SMA as reinforcement in composite plates at different temperatures is investigated. There are four different types of composite plate have been researched; two of them are SMA-based composite fabricated at 0° and 45° angles, and the other two are neat composite plate (without SMA wires) and plate built with local stiffener. The modal analysis testing is performed to determine the vibration characteristics of composite plates. This is followed by in-depth analysis of the temperature effects on the SMA-based composites in light of the fact that the temperature’s vital role in tuning the stiffness of SMA materials. The outcomes demonstrate that implanting SMA wires into composites increase the natural frequencies of the plate considerably, while decrease slightly for damping percentage. However, when SMA wires are heated, the damping percentage enhanced tremendously due to the phase transformation temperature of SMA from martensite to austenite. The conclusion of this study uncovers the potential of SMA materials in dynamic vibration control.

Keywords: Composite, shape memory alloy, modal analysis, vibration control

1. Introduction

Smart materials have been researched for a wide range of application due to their unique functional properties that draw great attention from researches [1–3]. One of the typical examples of smart materials is a shape memory alloy (SMA). The SMAs have engrossed in many applications due to its outstanding properties, such as a tuneable stiffness, high elasticity, high fatigue resistance and power density. As a matter of fact, SMA can be either a passive or active component when integrated with other structures to lessen harm caused by environmental impacts. Despite the fact that research activities of SMA applications in engineering structures are still in early laboratory stage, only a few is found viable and has been realised in actual fields [4–6].

Generally, SMA has a very unique feature known as shape memory effect; which brought about substantial recoverable deformations when SMA is heated. This capacity is created by martensite transformation to austenite phase that transpired in the material. Even though SMA is deformed at low temperature phase, it can recover its original shape by the reverse transformation upon heating to a critical temperature called the reverse transformation temperature [7].

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This characteristic displays a significant point of interest of SMA compared to other actuator materials as it has larger recovery force generated by phase transition when initial deformation is imposed. It is said that a maximum recuperation power of SMA can reach to 700 Mpa [8]. The generated power per unit volume is amazingly high which is 10 times higher than commercially available smart actuators such as traditional electro-hydraulic servo mechanical actuator and laminated PZT.

A preliminary study of weaving SMA wires has been reported by Boussu et al. [9]. They made the woven SMA fabric using Ni-Ti thin wires with 0.15 mm diameter. Unfortunately, the practical detail of the fabrication is not disclosed. Nowadays, embedding SMAs into composite materials have attracted attention from researchers around the globe [10–12]. SMA-based composites have the ability to change the material properties by inducing large internal forces in the materials and modify the structure’s stress and strain. These characteristics are found useful for structural vibration control. For example, in the study by Zhang et al. [13], they used SMA wires to control vibration and damping properties of laminated composites. Jinfene [14], on the other hand investigated the influence of SMA location on the composite plate where the greatest performance is observed when the SMA wires are fitted within the extreme layers of the plate. There are also researches have been done on composite with SMA short fibres. From Ni et al. [15], elasticity modulus was increased with more SMA short fibres. Similarly, the use of a SMA layer as actuator was studied by Ma et al. [16].

Nevertheless, there have been few studies concern with the vibration characteristics of the composite plate installed with SMA fibres at lifted temperatures. It has been explored in the research by Colakoglu that the temperature effects are extremely important in the determination of system frequency and loss factor [17]. This, consequently, could have significant impact upon system control which utilizing SMA material.

Therefore, understanding the temperature effects for the basic control utilizing smart damping treatment is of essential. In this paper, the significant of temperature control on the natural frequency, damping and mode shapes of composite plates installed with SMA wires are explored. The dynamic mechanical properties of composite plates were assessed by impact hammer modal testing. By measuring the fundamental mode of a composite plate, the effects of both SMA orientations and temperatures on the vibration characteristics of the plates can be resolved.

### 2. Preparation of Composite

The study utilizes the composite made of woven roving fiberglass installed into epoxy matrix. The weight fraction of utilized material composition was 50% fibre glass and 50% epoxy resin plus hardener. The chosen SMA wires was Ni-Ti-Cu alloy from Dynalloy Inc. with a diameter of 0.5 mm and maximum pull force of 34.94 N. In this work, a hand lay-up technique is applied for preparation of composite specimen. This approach is one of the types of wet lay-up procedure where it utilizes aged technologies in processing composite via an opening molding [18].

In this situation, the procedure of making layer by layer composite was made manually until the required thickness of composite is acquired. Fig. 1 illustrates the materials’ layer arrangement in the composite plate. Table 1 lists the engineering constants for polymer composite and SMA alloy employed in the study.

![Fig. 1 – Material layer arrangement in composite plate](image)

### Table 1 – Material constants [19]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Modulus’s Young (GPa)</th>
<th>Poisson ratio</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite</td>
<td>Ex: 12.9 Ey: 6.7</td>
<td>0.27</td>
<td>1161</td>
</tr>
<tr>
<td>SMA</td>
<td>20.4 Martensite)</td>
<td>0.30</td>
<td>6500</td>
</tr>
</tbody>
</table>

As previously stated, four types of composite plates were fabricated as categorized in Table 2 and illustrated in Fig. 2. Each plate has a similar dimension of 180 x 180 x 2 mm. The SMA wires which inserted in both of the composite plates are arranged in two different orientations which are 0° and 45° (refer Fig. 2). The weaving of SMA meshes are prepared by hand-made, though it was found hard to keep the quality of weft such as tension and pitch equal. As a result, a special apparatus is developed in the study to align and adjust SMA wires.

### Table 2 – Abbreviation of composite plates

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Plate without SMA wires</td>
</tr>
<tr>
<td>S2</td>
<td>Plate with local stiffener</td>
</tr>
<tr>
<td>S3</td>
<td>Plate installed with unidirectional SMA at 0° angle</td>
</tr>
<tr>
<td>S4</td>
<td>Plate installed with unidirectional SMA at 45° angle</td>
</tr>
</tbody>
</table>

![Fig. 2 – Type of composite plates and SMA wires orientation](image)
3. Procedure of Experiment

A modal analysis testing or known as free-free vibration arrangement is carried out in this study to determine the dynamic characteristics of the composite plates. Similar to our past study [20], sixteen grid points were produced on the plate as tabulated in Figure 3 to give acceptable spatial resolution for the global structural mode shapes. The roving impact hammer test was implemented with one single output of acceleration measured at point 1. The frequency response functions (FRF) for multiple inputs were measured using dBFa Suite software in the frequency range of 0–2000 Hz. The measured FRFs were curve fitted prior to be read in the MEScope software in Universal File Format [21].

![Location of measurement points on specimen plate](Image)

Fig. 3 – Location of measurement points on specimen plate

Basically, there were two types of experiment were carried out in the research: (1) The first experiment was to determine the effect of SMA material with respect to the vibration characteristic of composite when it was embedded in the composite plate at ambient temperature. The outcome of this result was compared to the other specimen types, such as neat plate and plate built with stiffener. (2) The second experiment was developed to verify the effect of SMA orientation at elevated temperature on vibration characteristic of SMA-based composites. A voltammeter was used to induce heat on SMA wires at four different temperatures. Fig. 4 shows the experimental setup for roving impact hammer test.

![Experimental setup for impact hammer test](Image)

Fig. 4 – Experimental setup for impact hammer test

4. Results and Discussion

4.1 Composite Plates at Ambient Temperature

The results of the natural frequencies and the corresponding damping characteristics of composite plates extracted from the modal analysis testing are tabulated in Table 2.

In this case, only the first five fundamental frequencies were observed, as these frequencies are significantly important to the dynamic behaviour of plate. It was found that the presence of epoxy resin in composite exhibits low stiffness which resulted a lower natural frequency for sample S1 particularly. By contrast, the natural frequencies for samples S2, S3 and S4 (refer Table 2 for abbreviation) was found increasing because of the additional mass to the plate, for example installation of local stiffener and SMA wires. Overall, it can be seen that sample S3 exhibits the highest natural frequencies of all modes.

In order to clearly demonstrate the effect of SMA wires, Fig. 5 displays the vibration characteristics of all composite plates obtained from the impact hammer modal testing. Only the first frequency mode was considered in this analysis since it was the most critical mode with relatively large displacement. Obviously, composite plates S3 and S4 which installed with SMA wires obtained a higher natural frequency value compared to the other type of composite plates. The result demonstrates the significant function of SMA wires by increasing the stiffness of composite plate although the other plates have a larger mass.

![Vibration characteristics of composite at first mode](Image)

Fig. 5 – Vibration characteristics of composite at first mode

In terms of damping ratio, sample S2 demonstrates a higher value compared to the others. It is elucidated that adding local stiffener to the plate reduces the plate's bending motion, and at the same time absorbing vibration movement. In contrast to plate embedding SMA wires, such as samples S3 and S4 decrease the damping ratio of composites extensively. It is noteworthy that different orientations of SMA wires produce significant damping effect to the composite plate. This outcome recommends that the structures with a high stiffness have a tendency to have a low damping percentage. And this is totally correct since the damping percentage is inversely proportional to the stiffness and mass of the structure as appeared in Equation (1).

\[
\zeta = \frac{c}{c_c} = \frac{c}{2\sqrt{km}}
\]  

(1)

Where \( c \) is damping coefficient and \( c_c \) is critical damping, \( k \) is stiffness and \( m \) is mass.

From all these results it shows that sample S3 produces the highest natural frequency value and the lowest damping percentage at the fundamental frequency mode. This displays that angle orientation of unidirectional SMA wires at 0° give a huge impact to the stiffness and critical damping of the composite plate. On the other hand, the corresponding mode shapes of the composite plates were computed using MEScope software. It was found that the mode shapes obtained are almost
similar and independent of the types of composite plates (only the first three mode shapes were displayed); whereby the first mode of free edges plate was found torsion and the remaining two are bending (refer Table 4).

### 4.2 SMA-based composites

Figs. 6 and 7 demonstrate the first mode natural frequencies and damping ratios of composite plates S3 and S4 which installed with SMA at elevated temperature. The outcome in Figure 6 shows that sample S3 has a higher natural frequencies compared to sample S4 at all implemented temperatures. The highest frequencies obtained was found at 40.5°C before slightly decrease at 50.5°C for sample S3. It was found that the reduction of natural frequency is brought on by phase transformation within SMA material to austenite region which in agreement with [22,23] that showed the phase transformation temperature for austenite of Ni-Ti-Cu alloy is ~50°C.

Thus this result concludes that the martensite phase of SMA increases the stiffness of composite material, but when it transforms to the austenite phase, it slowly decreases the material stiffness. By contrast, S4 shows reduction of natural frequencies till 40.5°C before increases at 50.5°C. This result clearly indicates the significant effect of SMA wires orientation on the stiffness of composite material.

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**Table 3 – Natural frequencies and damping ratio of composite plates**

<table>
<thead>
<tr>
<th>Mode of Vibration</th>
<th>Natural frequencies (Hz)</th>
<th>Damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
<td>S2</td>
</tr>
<tr>
<td>Mode 1</td>
<td>144</td>
<td>127</td>
</tr>
<tr>
<td>Mode 2</td>
<td>497</td>
<td>582</td>
</tr>
<tr>
<td>Mode 3</td>
<td>553</td>
<td>829</td>
</tr>
<tr>
<td>Mode 4</td>
<td>780</td>
<td>886</td>
</tr>
<tr>
<td>Mode 5</td>
<td>980</td>
<td>1390</td>
</tr>
</tbody>
</table>

**Table 4 – Natural frequencies and damping ratio of composite plates**

<table>
<thead>
<tr>
<th>Mode of Vibration</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td><img src="image1.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td><img src="image2.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 3</td>
<td><img src="image3.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Fig. 6 – Natural frequencies of composite plate embedded with SMA at the first frequency mode**

As aforementioned, one of the valuable qualities of SMA is their good damping property at super-elastic status. That is by installing SMA in one composite material, it can increase damping property of the composite. Figure 7 tabulates the result of damping percentage of SMA-based composites. It is shown that the damping percentage of sample S3 slowly increase as the temperature increases up to 50.5°C then it drops marginally.

A comparative pattern is observed for sample S4. This is explained by the hardening effect of austenitic phase transformation which starts at 50°C. A high stiffness in SMAs
within austenite phase at raised temperature will contribute to a low damping percentage for these samples [24,25]. Overall, it can be seen that the damping percentages obtained for sample S4 are much higher than S3 due to different orientation of SMA wires embedded in composite plates. These results uncover the capability of SMA in enhancing the damping properties of composite plates and control their natural frequency.

![Damping Ratio vs Temperature](image)

**Fig. 7** – Relationship between temperatures and damping ratio of composite plate embedded with SMA

5. Conclusion

This research study examined the functional of smart memory alloys (SMAs), its orientation embedded in the composite materials and the temperature impact on the vibration characteristics of composite plate. From the study, the implanted SMAs show a significant effect to natural frequency and damping percentage of composites due to the ability of shape memory effect. This is further concluded that the functionality and orientation of SMAs embedded in composite plate play important role in controlling vibration response because different orientation of SMA wires can produced different natural frequency and damping percentage. The temperature is also found to play role on system natural frequency and damping percentage of the composite plate as both martensite and austenite phase of SMA show strong effects in their stress–strain curves for loading-unloading cycles and dissipation of energy. Upon heating, the embedded SMA wires increase the stiffness of the structure, thus can actively tune the structure's natural frequency. By tuning the natural frequency, the resonance frequency of the structure can be avoided, as well as to reduce the structural vibration at its resonant frequency. So, this is the basic principle of SMAs for active structural vibration control. If it combines with the application of the damping control, the SMA wires may reduce the vibration levels of the structure significantly.

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