ORIGINAL ARTICLE

Effect of Sensor Location of Smart Composite Plate System on Feedback Control Performance

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Abstract: The present study is proposing a deflection control of a fiberglass composite plate system using shape memory alloy (SMA) actuators. The aim of this study is to determine the optimal placement of sensor for the feedback smart composite plate system. Strain measurement on the composite plate was chosen as the input variable for the feedback system. The change in strain on the composite plate was different at all locations on the plate during deflection. Thus, six strain gauges were placed at three positions i.e. tip, mid and root of the plate, at angle 0° and 45° in order to measure the change in strain at these locations and determine which is the best location to produce accurate control of the plate. The performance of the plate using these input variables were compared and analyzed by conducting experiments which required the plate to be deflected using the control system. In order to evaluate the performance of the controller under varying conditions, disturbances were also added to the experiments. The disturbances introduced were similar to those faced by aircraft during flight that is wind flow at varying velocities conducted in the wind tunnel. From the experimental results, it was found that the tip of the plate had the highest change in strain value and the control using input from the strain gauge located there produced the best performance as compared to input from strain gauges located at mid and root of the plate. However, in the presence of airflow, it was found that the best control performance was using feedback from the strain gauge located in the middle of the plate.

Keywords: Smart structure system, Shape memory alloy, Strain feedback control, Composite

1. Introduction

Smart and intelligent systems are fast taking over all aspects of our life. Automatic is no longer deemed sufficient, as adaptive becomes the new requirement in current technologies. In the aviation and aerospace industries, researchers are also geared towards this objective, fueled by the advancement of technology and availability of smart materials that make it possible to achieve this pursuit. One such example is the morphing wing, which allows wing to change its geometry through flight in order to produce optimum performance throughout different cruise conditions. Presently there are numerous ongoing researches on morphing wing design, which is deemed to be the breakthrough innovation to drive the future, next generation aircraft[1,2]. Although numerous conceptual design of morphing wing has been generated, it will take some time before we can see its application in a commercial flight due to lack of support from manufacturers and end-users as they remained unconvinced that the cost of its implementation outweighs the potential benefits of its implementation.

The present study is proposing an optimal feedback variable for deflection control of a single cantilevered composite plate system for morphing wing application

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by improving its performance through better selection of the feedback variable and ensuring that the performance is robust even in the presence of disturbances such as air flow and vibration. Shape memory alloy (SMA) is one type of smart material that is suitable to be used as actuators in such design due to its ability to be actuated to modify the shape of the structure. It is considered superior to other smart materials due to its efficiency and large energy storage capacity[3]. Shape memory alloy can be used in shape control due to its high recovery forces and large displacement[4-6]. Currently there are numerous morphing wing design that uses SMA as actuators[7,8]. However, there are some disadvantage in using SMAs such as nonlinear response of the strain to input current and hysteresis characteristic as a result of which their control is inaccurate and complicated. And in the case of morphing wing, the use of structure that is capable of enduring the prescribed loads but at the same time is flexible to morph or change its shape, further complicates the design solution. Due to the complexity of the morphing wing system, it is still unclear which input variable that will produce the best performance.

Lima et. al conducted an experiment investigation on analysis and control the strain of flexible aluminum beam under external disturbances[9]. Here strain gauge was used to measure the strain of the beam and SMA wire was used as actuators. PI (proportional-integral) controller has been used to control the strain of aluminum beam. In this study shaker was used to produce disturbance during testing. One strain gauge was used and placed in the middle of the beam. Under external disturbances, it was demonstrated that the developed PI control system operates well. It was shown that the electro-dynamic shaker could be used up to some extend or with limitation. It was found with a lower frequency, the external disturbance restricted the action of the PI controller due to its frequency which was slightly higher. Bil et. al proposed a morphing wing control using SMA actuator [10]. For this study, smart material was used and it is suitable candidate for adaptive airfoil design as SMA can be activated to alter the airfoil shape. It is light weight and produce large deflection and high force which make it perfect choice for actuator. For the deflection of wing camber SMA actuator was used by means of resistive heating of actuator and cooling in surrounding air. In this study, a wind tunnel test was performed to analyze the change in lift-to-drag ratio when the actuator is switched on and off. In the result, it shows that the SMA actuators were reliable as significant change in lift-to-drag ratio was detected when the wing morphed.

Due to the behavior of the SMA actuator and composite structure, which are affected by the disturbance that occurs during flight such as wind flow, it will be critical to ensure that the fiberglass composite plate-like wing system can perform effectively even in the presence of disturbances. The presence of these disturbances to a morphing wing system using SMA actuator might reduce the effectiveness of such system since the external environment affects the behavior of SMA. If the control performance reduces significantly, a disturbance rejection method needs to be added to the morphing wing system design. Experimental testing using wind tunnel was used to obtain the results of the control performance in the presence of disturbance. The results were analyzed to determine the optimal feedback variable for the smart composite plate system.

2. Composite plate system using Proportional-Integral-Derivative (PID) Controller

Prior to the experimental work, the smart composite design utilized finite element method in order to gauge the structural response actuated by the SMA. Different configurations were analyzed by changing the properties of the composite material, the position of the SMA actuators within the structure and forces exerted by it on the structure. Placement of the actuator was critical in obtaining the desired plate displacement. The design objective was to produce a plate that can be displaced at least 10 mm along the z-axis at the tip. A different combination of applied forces by the SMA actuator was analyzed. The analysis was repeated for different SMA actuator configuration. It was found that the number of SMA actuators used and orientation produced significant variation in plate displacement [11].

An experimental test bench was designed to analyze the performance of a smart structure system composed of composite laminate plate with shape memory alloy (SMA) actuators placed on the surface of plate[12]. The smart composite design utilized finite element method in order to gauge the structural response actuated by the SMA. Different configurations were analyzed by changing the properties of the composite material, the position of the SMA actuators within the structure and forces exerted by it on the structure. Placement of the actuator was critical in obtaining the desired plate displacement. The design objective was to produce a plate that can be displaced at least 10 mm along the z-axis at the tip. The SMA wires used in the prototype were FLEXINOL® wires which were precrimped with ring crimps produced by Dynalloy Inc. In order to meet the displacement criterion, a wire length of 355mm was chosen since the SMA wires can contract 5% to 8% of their original dimension. A single wire actuator has a pull force of 1250g, so in theory, 3 wires connected mechanically in parallel has a total pull force of at least 37N.

The strain gauge used for this experiment was of type F-35-12 T11P15W3, part no. 528 quarter-bridge with resistance of 120 ohms and gage factor of 1.98. It was mounted on the upper surface of the composite plate. The strain measurement was captured by LABVIEW and used as the input measurement to the control system. The SMA actuated composite schematic in shown in **Figure 1.** Six strain gauges placed on the plate surface; Tip 0^0 , Tip 45^0 , Mid 0^0 , Mid 45^0 , Root 0^0 and Root 45^0 . SMA wires were instilled on the plate.

A controller was needed for the morphing of composite plate to attain good tracking performance. Accurate shape control was difficult not only due to the nonlinearities but also the slow cooling of the SMA actuators. In the morphing of plate application, the effectiveness of the controller is crucial. Due to the nonlinear behavior of the SMA, the choice of the variable to be measured and feedback is very significant in the development of the controller for an SMA actuator.

Strain and deflection were the two parameters that had to be measured. The relationships between strain measurements at different location and the deflection are shown in **Figure 2**, where the deflection was measured at the free end of the plate. These data were useful in the development of the controller, as the strain of the composite plate were used to control the deflection of the plate. However, during post-processing, it was important to have the true strain measurements in order to establish the change in the plate's shape. The initial results showed that the relationship between the plate’s deflection and the strain measurements in the middle and the tip of the plate were linear.

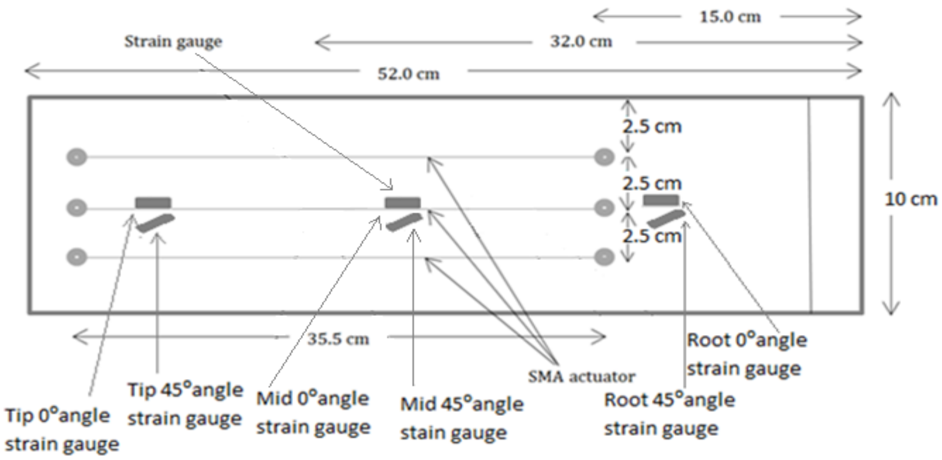
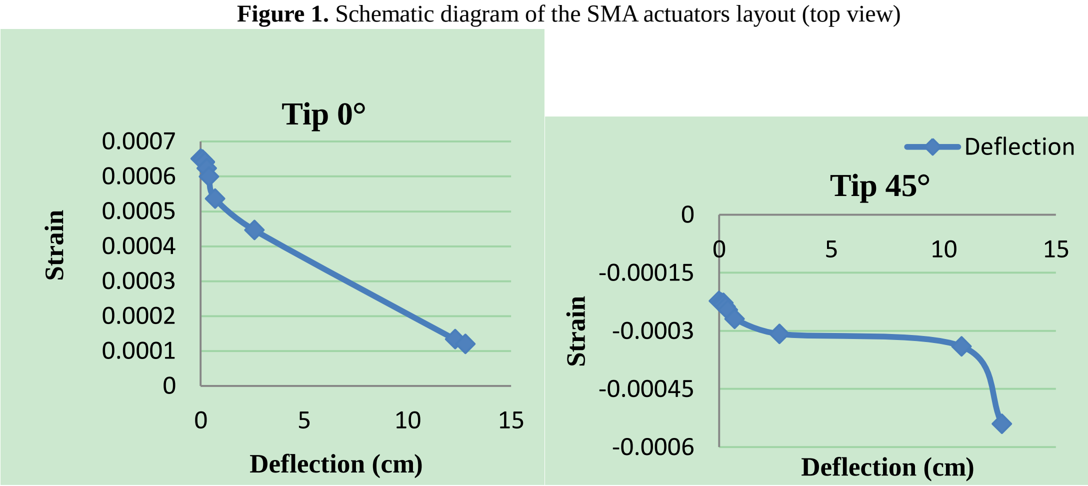


Figure 1. Schematic diagram of the SMA actuators layout (top view)



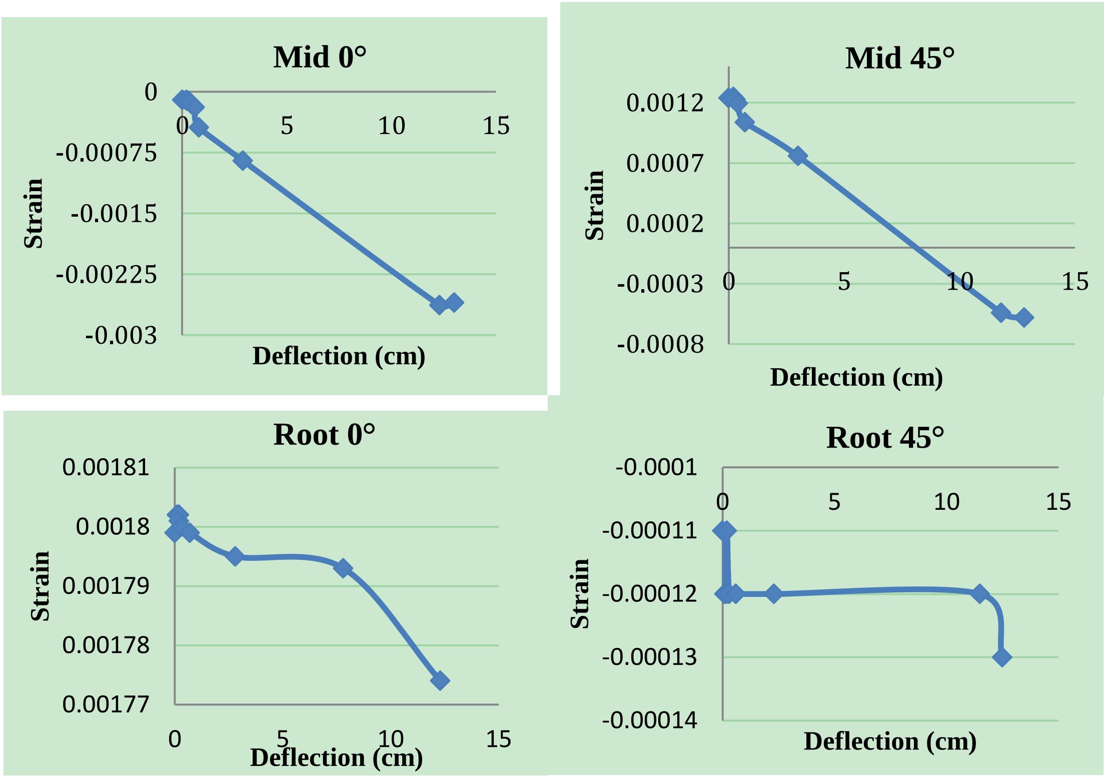


Figure 2. Strain vs Deflection Graphs

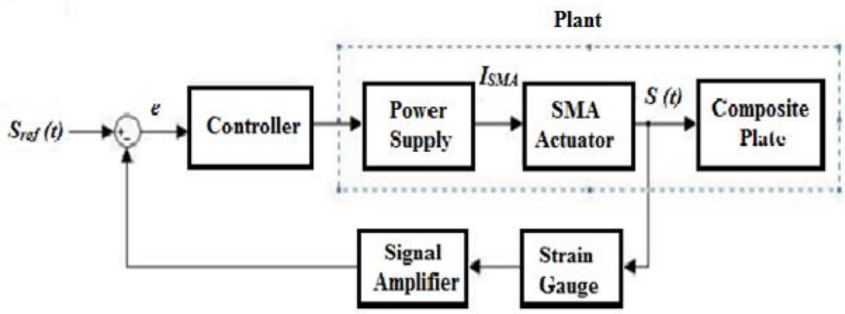


Figure 3. Feedback control system for the smart structure

For morphing of plate using strain feedback control, the strain generated on the plate surface during morphing was used as the input to the feedback system. The strain changed as the shape of the plate was altered when the actuator was heated with electric current. To reach the desired shape of the plate, the controller regulated the electric current to the actuators. A feedback control structure was proposed for the morphing of composite plate as shown in the block diagram in **Figure 3.** The input of the control system is $S_{ref(t)}$ which was the reference value for the morphing of the plate. S(t) is the actual output of the control system and it corresponded to the strain generated over the plate detected by the strain gauge which was placed on the upper surface of plate at three different locations which were tip, mid and root. e is the control error and corresponded to the difference between S(t) and $S_{ref}(t)$.

If the control error e = $S_{ref}(t)$ - S(t) is positive, that is the strain of the actual plate deflection S(t) is smaller than the desired strain, $S_{ref}(t)$, the controller generates a signal I_{SMA} which turns the actuator on, permitting electrical current to flow through the SMA wire. The temperature of the SMA wire starts to increase, when current flows through the wire due to the Joule effect produced by the electrical current. As the martensite to austenite phase transformation start temperature is reached, the wire starts to recover its high-temperature shape (shorter length) or contracted, creating a moment and generating a force which deflects the plate until it reaches the reference value $S_{ref}(t)$. On the other hand, if e is negative, that is if the strain on the upper surface of the plate S(t), is larger than the desired strain, $S_{ref}(t)$, the controller turns the actuator off by cutting the electrical current supply so that the actuator is cooled by the surrounding air.

In designing the best controller for this system, some methods were analyzed. Since the potential of using PID control for an SMA actuator has not been thoroughly investigated, it seems to be a good starting point. The PID controller is the most frequent form of feedback with more than 95% of the control loops in process control being of PID type, where most loops are actually PI control[13].

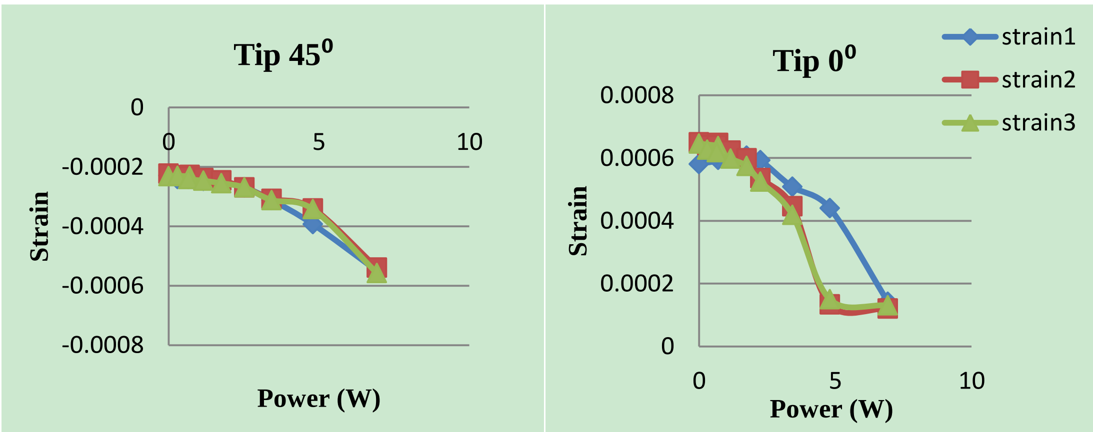
PID is easy to be implemented as it is well-known to all control engineers and there are many techniques to tune the controller, moreover through experiments or theoretically[14]. In addition, it is fairly easy to use it on a field programmable gate array (FPGA) which offers a real-time control at a high sampling rate[15]. Generally, the application of a standard PID controller is restricted by the constraint of the industrial control system[14,15]. For the morphing of plate developed here, the limitations are the phase transition of SMA and limiter of the heating power. The PID controller was designed and implemented in the experimental setup to control the smart composite plate. Results from the earlier experiments illustrated that the smart structure system that has been designed performed effectively and the strain value of the composite structure can be controlled accurately[12].

5. Experimental setup

The purpose of the experiment was to actively control the morphing (shape changing) of the composite plate actuated by the SMA actuators in the presence of external disturbances. Data acquisition board (DAQ) was used for the process of obtaining data from sensors and sending the data into the computer for processing[16]. The input sensor was connected to a data acquisition board via signal conditioning. The data acquisition (DAQ) board is a printed circuit board which supplies a multiplexer, amplification, analogue-to-digital conversion, registers and control circuitry for analogue inputs in order for the computer to make use of the sampled digital signal. In the experiment, the data acquisition board used was NI cDAQ USB-9174, manufactured by National instrument. An analogue output NI USB-9263 was used to send signal to the power source with a range of 0-20 V or 0-10 A, to supply current to the SMA actuators.

The power supply unit provided the current intensity through an analogue signal from a control program implemented in LABVIEW. The voltage was set between 0V to 8V and the maximum current was 0.5A to avoid overheating of the SMA actuators. A sensor was used to detect the change in measurement which corresponded to the deflection of the plate when the actuator was turned on and provided signal as feedback to the control system. The signal was then compared to the target that had been set in the controller. The controller turned off the current when the actuator achieved the desired deflection and the SMA was cycled in endless heating/cooling cycles through the controller switching command on/off of the current in order to maintain the composite plate’s deflection.

In the static test the plate was deflected manually by supplying power and the relationship between strain and power was established. The test was repeated to ensure the repeatability of the measurements. The results can be used to determine the required power for different strain measurement and it is shown in **Figure 4.**



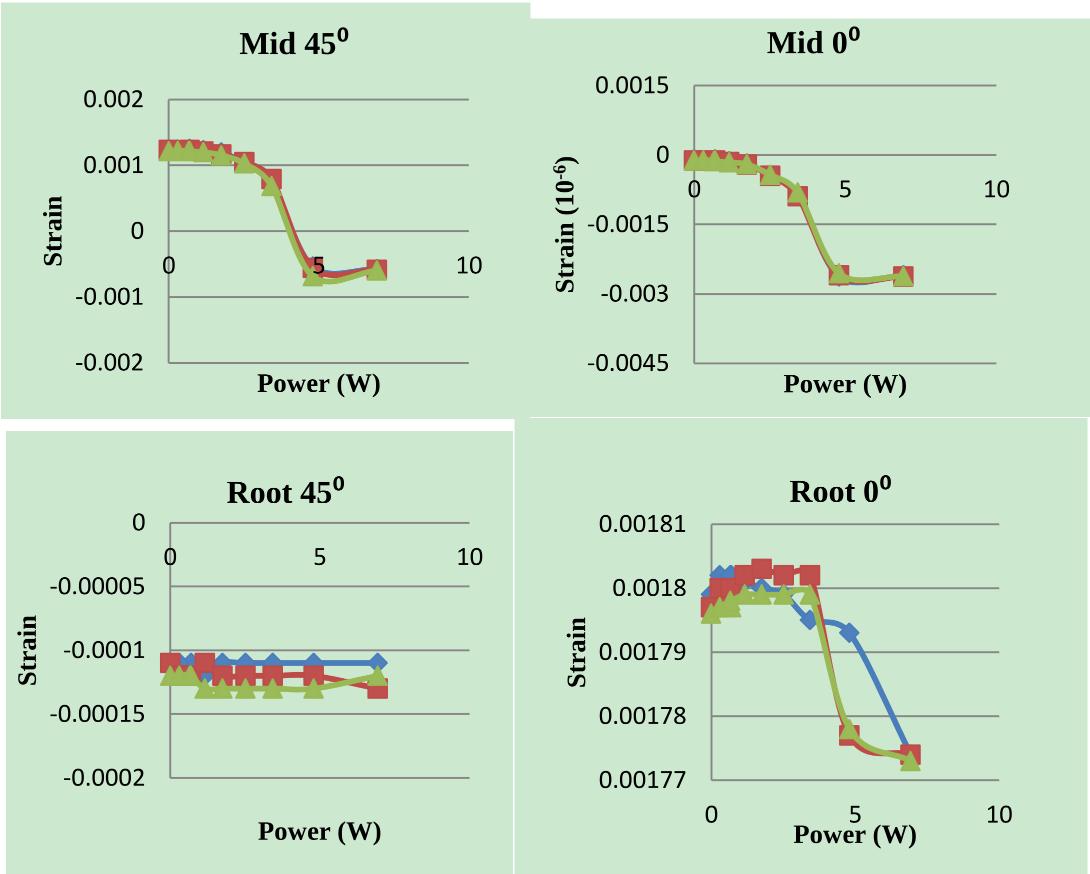


Figure 4. Change in strain measurement of composite plate with power

Figure 5. Wind tunnel experimental setup

The SMA actuated composite plate system was tested in the presence external disturbances such as those occurred during flight, to analyze the performance of the composite plate system and to ensure the robustness of the system. The wind tunnel was used to observe the performance of the plate when it comes in contact with air while the shaker was used to observe the performance of the plate when vibration occurs.

The objective of the wind tunnel tests was to analyze the performance of actively controlled plate under varying airflow velocities using strain feedback. The air flow velocities used in the experiments were 2m/s and 4m/s. The Universiti Putra Malaysia Aerospace Wind Tunnel is an open-loop low speed wind tunnel with a maximum speed of 50 m/s. The test section dimensions are 1000mm (wide) x 1000mm (high) x 2500mm (long).

The maximum available power is 75HP, with anti-turbulent screen and 10 pieces of blades, overall length of wind tunnel is 14.5m and the overall height is 4m. **Figure 5** shows the experimental setup of plate in the wind tunnel.

The plate was placed in the wind tunnel in horizontally as shown in **Figure 6.** The strain at different location of the plate was varied to observe how the plate deflected under different wind velocities. The desired strain measurement was varied by an increment of 50 µstrain.

6. Results and Discussion

6.1 Results for experiments with feedback control

The composite plate was required to deflect and maintain its shape by tracking 50 µstrain and 100 µstrain step input using input from strain gauge located at various location of the plate. It was observed that the plate followed the step command closely upon heating where it deflected by 50 µstrain and 100 µstrain when the feedback system used the input obtained from the strain gauge located at the middle and tip of the plate as shown in **Figure 7** and **Figure 8.** The composite plate failed to follow the input command when the strain gauge located at the root of the plate was used to provide input signal to the feedback system. For the feedback system with inputs from strain gauges located at the middle of plate and 0 strain gauge located at the tip, the response time was very fast and reached the desired strain value in less than 5s for the tracking of 50 µstrain step input and less than 10s for the tracking of 100 µstrain step input. However, the response using feedback input from the strain gauge located at mid plate produced larger overshoot compared to the response using feedback input from the 0° strain gauge located at the tip. The overshoot for the 50 µstrain step response for was 26%, 74% and 82% for the feedback using input from (a) Tip 0°, (b) Mid 0° and (c) Mid 45° strain gauges, respectively. The steady state error for all step was 0% for the response using feedback input from both strain gauges located at mid plate and the 0^0 strain gauge located at the tip of the plate.

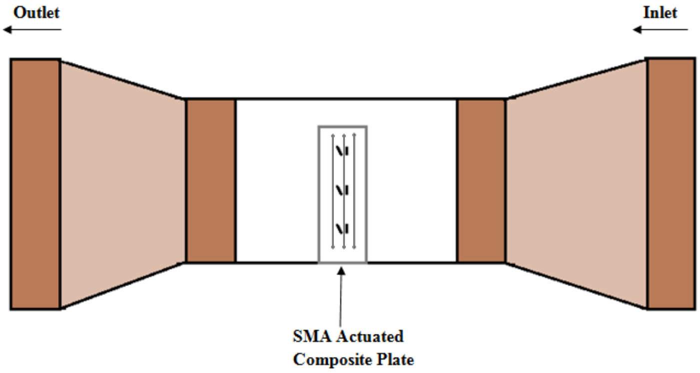
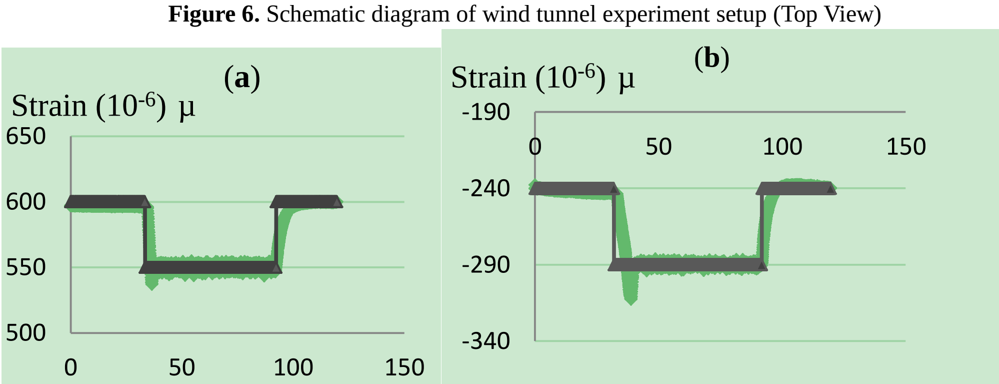


Figure 6. Schematic diagram of wind tunnel experiment setup (Top View)



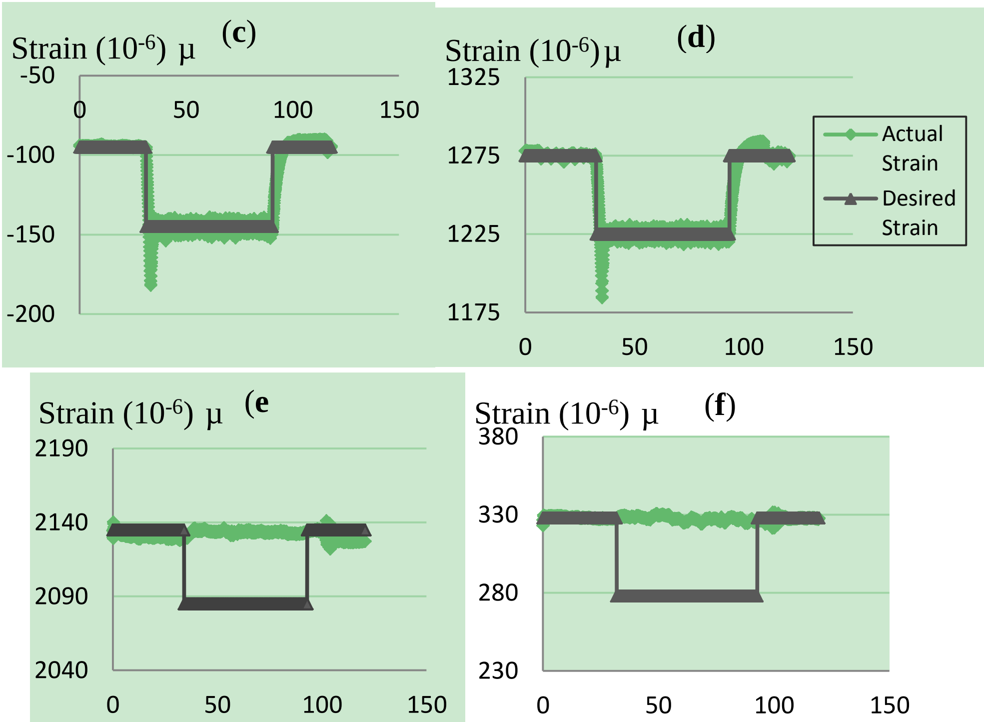


Figure 7. Response curve for 50 µstrain step input function using input signal from strain gauge at various locations: (**a**) Tip 0 °, (**b**) Tip 45 °, (**c**) Mid 0 °, (**d**) Mid 45 °, (**e**) Root 0 °, (**f**) Root 45 °

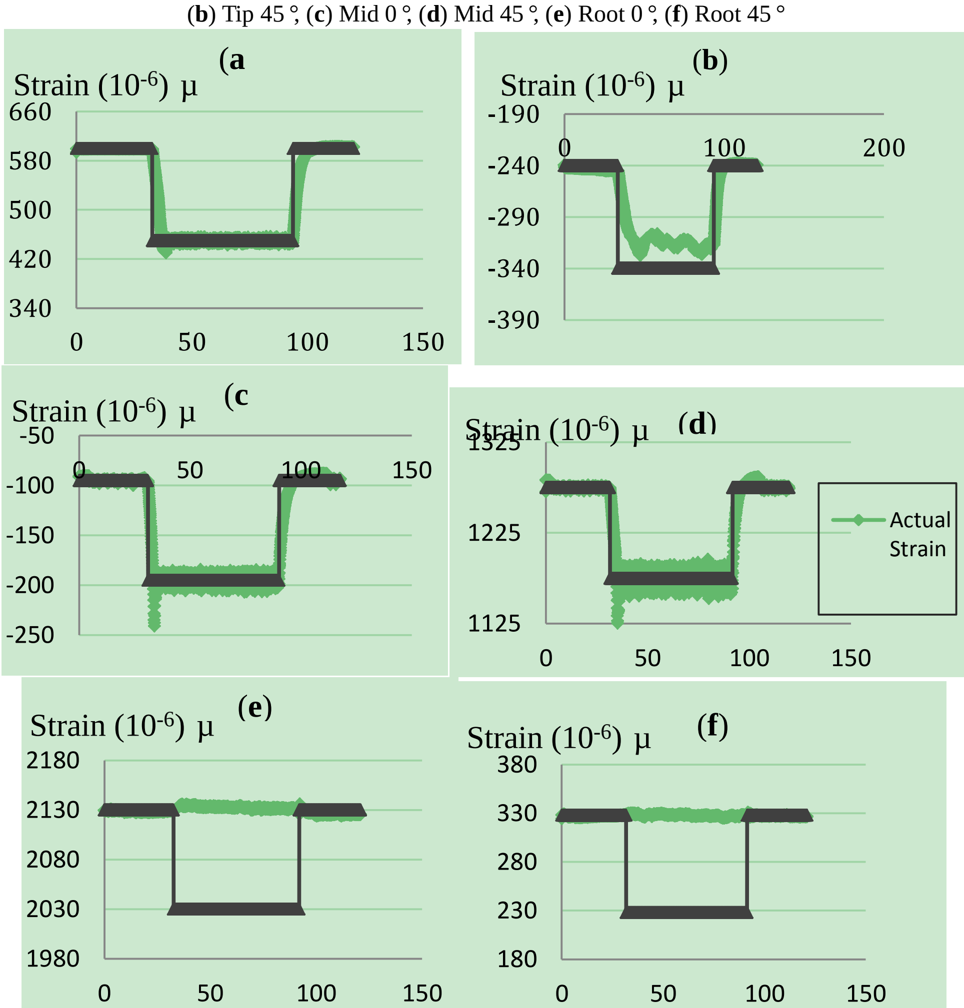


Figure 8 Response curve for 100 μstrain step input function using input signal from strain gauge at various locations: (**a**) Tip 0 °, (**b**) Tip 45 °, (**c**) Mid 0 °, (**d**) Mid 45 °, (**e**) Root 0 °, (**f**) Root 45 °

The strain and the change in strain on the composite plate during deflection were not equal at all location because the acting force was not equally distributed along the plate. Since a cantilevered plate was used the root has the smallest change in strain thus it was almost impossible to control using input from a strain gauge at this location. The results show that the best response with minimum overshoot was obtained for the feedback using input from the 0° strain gauge located at the tip of the plate. **Figure 9** shows the desired strain and the realized strain which corresponded to actual strain measurements on the surface of the composite plate; and the time histories of the critical parameters for the feedback using input from the 0° strain gauge located at the tip of the plate. For the 50 µstrain step input, the response was fast and it reached the desired strain value in 2s, however this resulted in a high overshoot of 26% as shown in **Figure 9a**. The temperature reached a peak of 37 ℃ during the contraction of SMA which produced the force for maximum deflection corresponding to 50 µstrain. For the 100 µstrain step input, the response time was longer where it took almost 5s to reach the desired strain value, but this resulted in a lower overshoot of 20% as shown in **Figure 9b**. The temperature reached a peak of 46℃ during the contraction of SMA which produced the force for maximum deflection corresponding to 100 µstrain. For the strain feedback composite plate system, the average voltage during steady state increased as the step value increased. For 50 µstrain step input the voltage reached the maximum value of 8V and after 1 second reduced to 2.7V during steady state. For 100 µstrain step input the voltage reached the maximum value of 8V and after 1 second reduced to 3.5V during steady state.

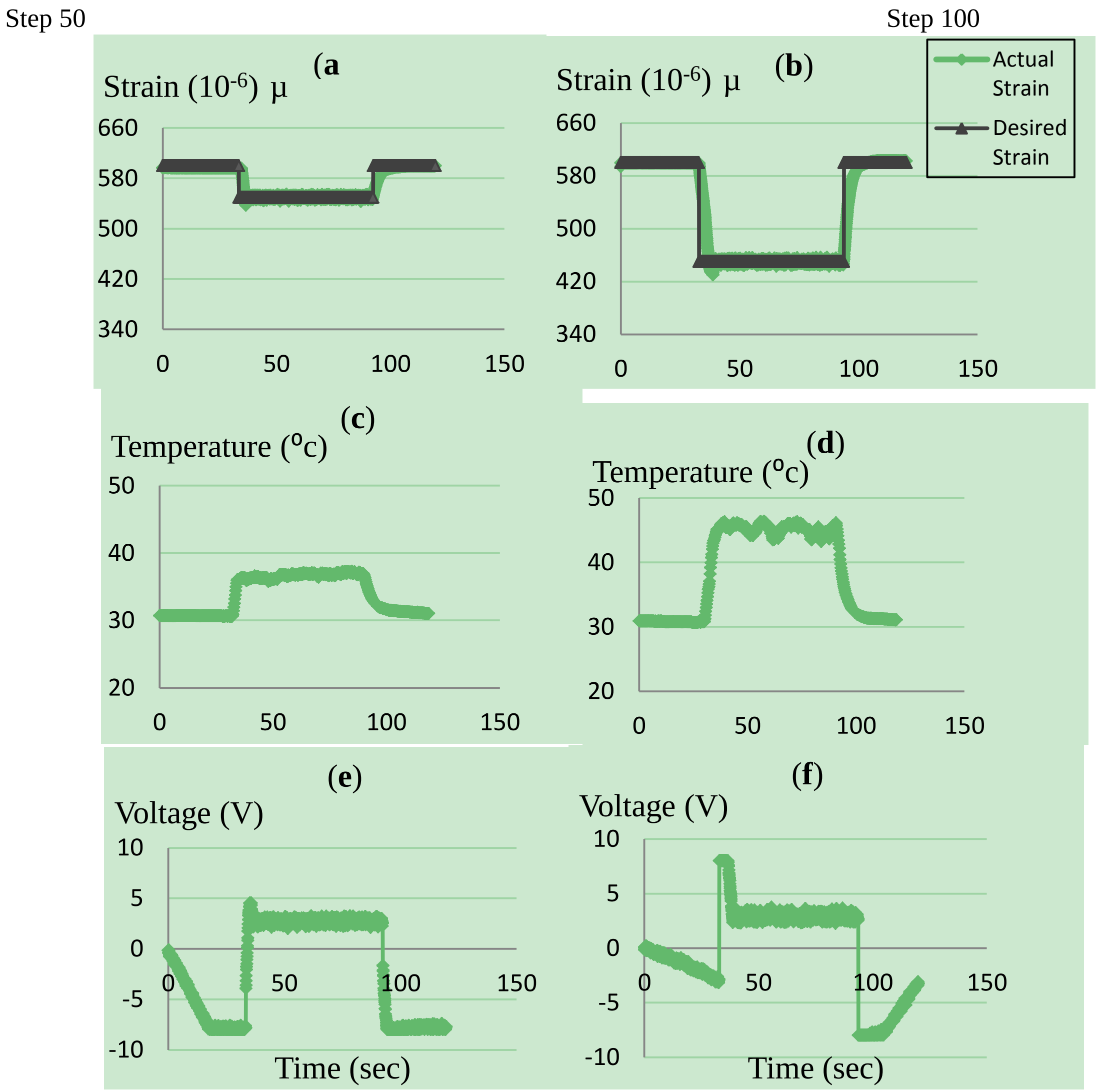


Figure 9 Response curve for 50 µstrain and 100 µstrain step input function using input from strain gauge located at tip 0°: (**a**) and (**b**) actual and desired strain measurement, (**c**) and (**d**) temperature of SMA wire and (**e**) and (**f**) voltage signal from controller

6.2 Results for experiments in the wind tunnel

In the wind tunnel experiments, the smart composite plate was tested under different air velocities of 2m/s and 4m/s. For the experiments conducted in the wind tunnel the composite plate was required to deflect and maintain its shape by tracking step input from 0 to 50 µstrain using the controller with input measurement from the strain gauges at various locations. It was observed that the plate followed the step command closely upon heating where it deflected by 50 µstrain when the feedback system used the input obtained from the strain gauge located at the middle and tip of the plate as shown in **Figure 10** and **Figure 11.** The composite plate failed to follow the input command when the strain gauge located at the root of the plate was used to provide input signal to the feedback system.

The step response for the plate deflection was accurate with 0% steady state error when the air velocity was 2m/s when input from the tip 0^0, mid 0^0 and mid 45^0 strain gauge was used as shown in **Figure 10a-Figure 10c**, but when the air velocity was increased to 4m/s, the smart composite plate system did not achieve the desired strain as shown in **Figure 11a-Figure 11c**). In the presence of 2m/s air velocity, the response time was very fast and the plate reached the desired strain value in less than 5s, which resulted in a 32% overshoot shown in **Figure 10a**. The smart composite plate was unable to obtain the desired strain value and there was no overshoot in the presence of 4 m/s air velocity as shown in **Figure 11.**

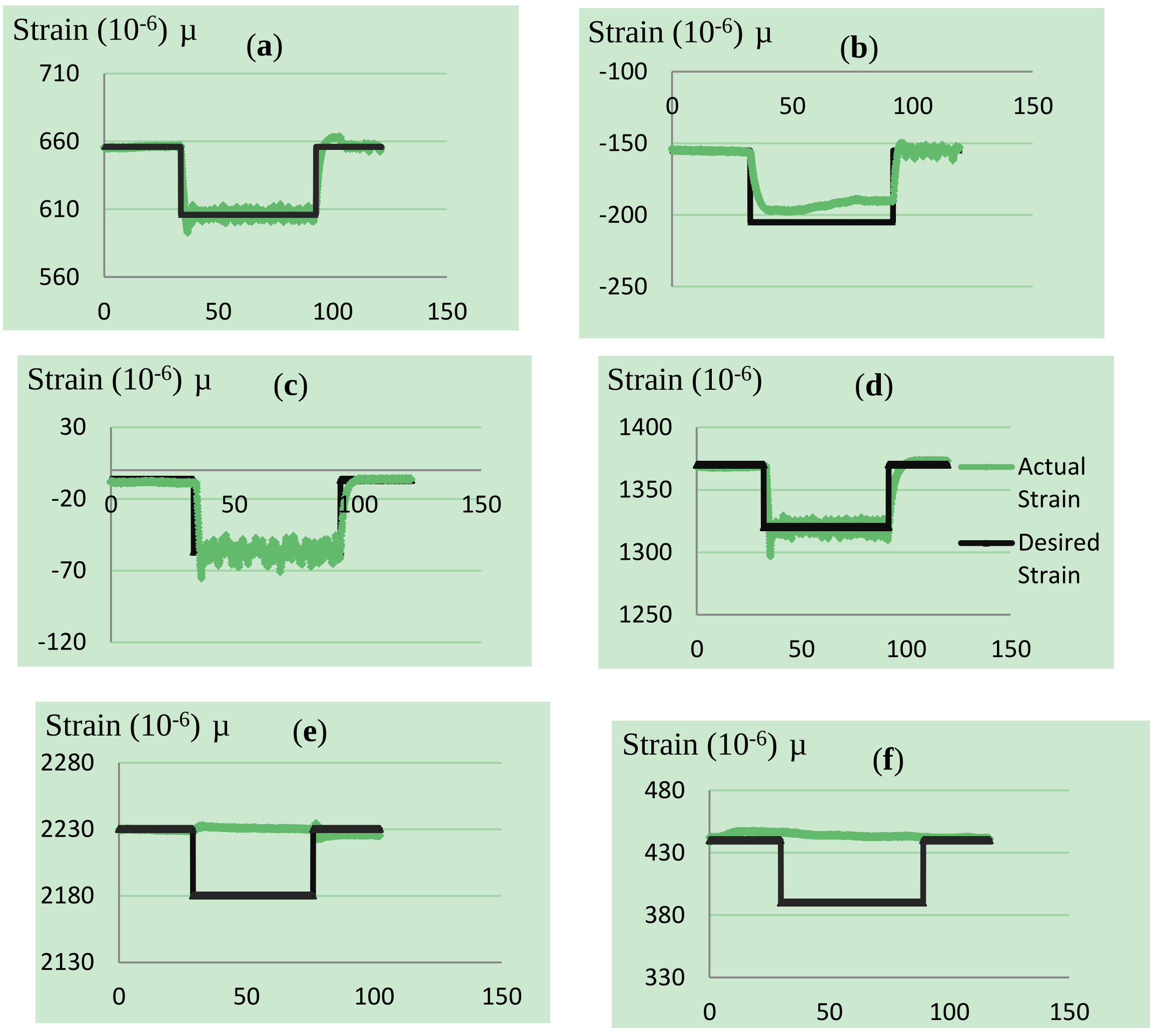


Figure 10 Response curve upon 50 μstrain step input function under 2 m/s wind flow using input signal from strain gauge at various locations: (**a**) Tip 0 °, (**b**) Tip 45 °, (c) Mid 0 °, (**d**) Mid 45 °, (**e**) Root 0 °, (**f**) Root 45 °

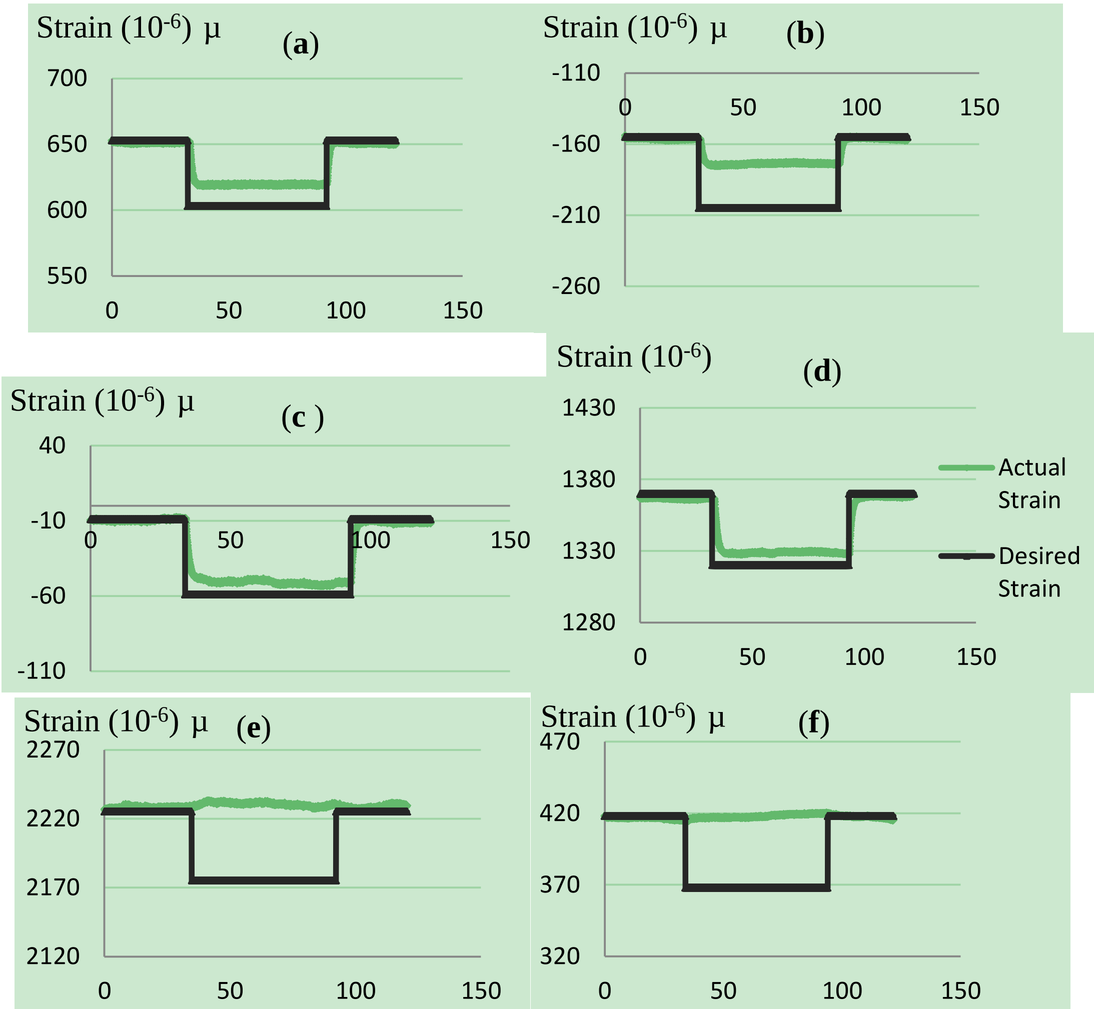


Figure 11. Response curve upon 50 μstrain step input function under 4 m/s wind flow using input signal from strain gauge at various locations: (**a**) Tip 0 °; (**b**) Tip 45 °; (**c**) Mid 0 °; (**d**) Mid 45 °; (**e**) Root 0 °; (**f**) Root 45 °

The results from the wind tunnel experiments show that the best response with minimum overshoot was obtained for the feedback using input from the 0 ° strain gauge located in the middle of the plate. **Figure 12** shows the desired strain and the realized strain which corresponded to actual strain measurements on the surface of the composite plate; and the time histories of the critical parameters for the feedback using input from the 0 ° strain gauge located in the middle of the plate. The response was fast and it reached the desired strain value in 2s without overshoot as shown in **Figure 12a- Figure 12b**. The steady state errors for the response with 2m/s wind velocity was 0% and more than 10% for 4m/s wind velocity. It can also be observed that as the wind velocity increased the temperature of SMA decreased, thus the plate was unable to achieve the desired strain value as shown in **Figure 12c-Figure 12d**. The voltage graphs show the voltage signal sent out by the controller in response to the input error. Higher voltage was required by the controller to deflect the plate as the wind velocity increased as shown in **Figure 12e-Figure 12f**. At 2 m/s wind velocity, the voltage required to deflect the plate was approximately 3V, and this value increased to 7V when the wind velocity increased to 4m/s.

From the results of the wind tunnel experiments, it is shown that the composite plate under the disturbance of air flow can be controlled effectively when the air velocity is low at 2 m/s using feedback from the strain gauges located at the middle and the tip of the plate. As the velocity of air increased, it was more difficult for the plate to be deflected to produce the desired strain due to the wind loading on the plate and the cooling of the SMA by the air flow. The SMA wires were exposed on the plate which affected its performance and caused the SMA temperature to decrease as the wind velocity increases. As the temperature decreased the SMA was not able to create sufficient force to deflect the plate. In order to improve the performance, the SMA actuators have to be covered or embedded in between the layer of composites.

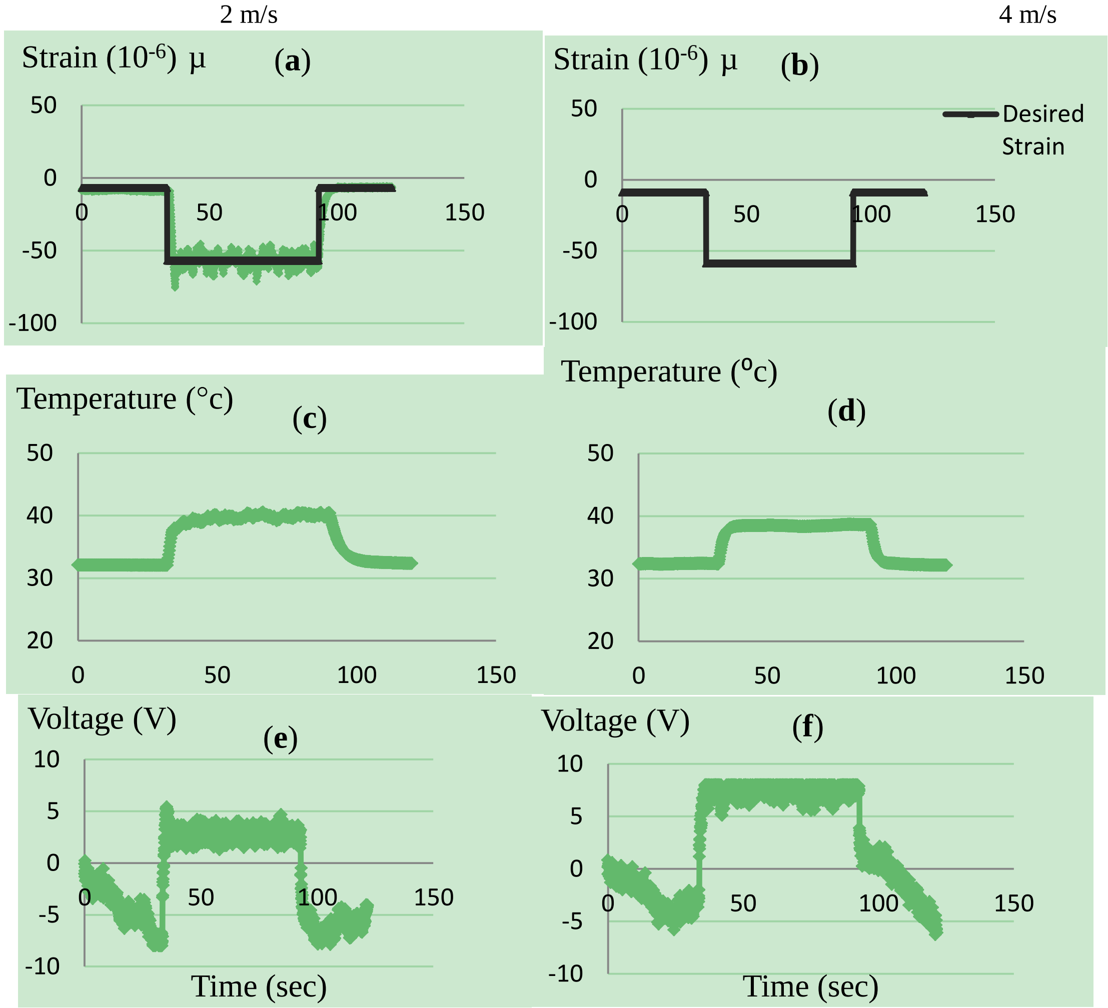


Figure 12 Response curve for 50 μstrain step input function under 2m/s and 4m/s wind flow using input from strain gauge located at mid 0º: (**a**) and (**b**) actual and desired strain measurement, (**c**) and (**d**) temperature of SMA wire and (**e**) and (**f**) voltage signal from controller

7. Conclusion

Experiments have been conducted to study the effect of the different sensor placements on the performance of SMA actuated composite plate. Another aim of this study was to investigate the performance of SMA actuated composite plate under external disturbances (varying air flow and vibration). In the experiments, the smart composite plate was required deflect and maintain its shape by tracking a step input of 50 μstrain, 100 μstrain and continuous step input. After analyzing the performance of composite plate using the controller, it was tested under some external disturbances such as air flow. In the wind tunnel experiments, the plate was tested under 2m/s and 4m/s.

The smart composite plate was able to follow the input command effectively when it was required to reduce or increase the strain on its surface. Using input from the strain gauge located at the tip was also possible to be controlled but there was some limitation. However, it was quite difficult to control the plate using input from strain gauge located at the root due to its location near the clamping area.

From the results, it can be concluded that the placement of sensor on the plate also affected the performance of the control system. The system using sensor placed at mid part of plate performed well, however when using the sensor placed at tip and root of the plate did not provide satisfactory performance. In the control experiments the percentage overshoot for mid 0^0 was around 25% and for mid 45^0, tip 0^0, and tip 45^0 it was less than 10%.

Research investigated the optimal placement of strain gauge to emphasize the control performance of SMA actuated composite plate system. The smart composite system was also analysed in the presence of disturbances such as those occurs in real flight. Placement of multiple sensors on the composite plate can improve the control performance and allow accurate morphing of the composite plate. In order to improve the smart composite's performance, the SMA actuator has to be embedded inside the layer of composite or it may be integrated with polydimethylsiloxane (PDMS) to improve cooling. The composite plate system may be implemented on a UAV wing by placing strain gauge in the middle of the wing span.

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References

1. Barbarino S., Bilgen O., Ajaj R. M., Friswell M. I. and Inman D. J., "A Review of Morphing Aircraft," Journal of Intelligent Material Systems and Structures, Vol. 22 (9), pp. 823-877, 2011.
2. Sofla A.Y.N., Meguid S. A., Tan K. T. and Yeo W. K., "Shape Morphing of Aircraft Wing: Status and Challenges," Materials and Design, Vol. 31(3), pp 1284-1292, 2010.
3. Fontanazza F., Talling R., Jackson M., Dashwood R., Dyeand D. and Iannucci L. "Morphing Wing Technologies Research," Seas DTC First Conference, 2006.
4. Choi, S. and Lee, J. J. "The Shape Control of a Composite Beam with Embedded Shape Memory Alloy Wire Actuators," Smart Materials and Structures, Vol. 7 (6), pp. 29-38, 1998.
5. Oh, J. T., Park, H. C. and Hwang, W. "Active Shape Control of a Double-plate Structures using Piezoceramics and SMA Wires," Smart Materials and Structures, Vol. 10 (5) pp. 1100-1106, 2001.
6. Yang, S. M., Roh J. H., Han J. H. and Lee I. "Experimental Studies on Active Shape Control of Composite Structures using SMA Actuators," Journal of Intelligent Material Systems and Structures, Vol. 17 (767) DOI: 10.1177 / 1045389X06055830, 2006.
7. D J Hartl and D C Lagoudas, "Aerospace applications of shape memory alloys," Proc. IMechE Vol. 221 Part G: J. Aerospace Engineering, pp. 535-552, 2007.
8. S. Barbarino, E I Saavedra Flores,5, R. M. Ajaj, I. Dayyani and M I Friswell, A review on shape memory alloys with applications to morphing aircraft," Smart Materials and Structures, Volume 23, Number 6, 063001 (19pp) 2014.
9. Lima W. M., de Araujo C. J., Valenzuela W. A. V. and da Rocha Neto J. S., "Control of Strain in a Flexible Beam Using Ni-Ti-Cu Shape Memory Alloy Wire Actuators," Journal of the Brazillian Society of Mechanical Science & Engineering, Vol. 34, pp.413-422, 2012.
10. Bil C., Massey, K. and Abdullah E. J., "Wing Morphing Control with Shape Memory Alloy Actuators," Journal of Intelligent Material Systems and Structures, Vol. 24 (7), pp. 879-898, 2013.
11. D. L. Majid, E. J. Abdullah, N. F. Harun, G. Y. LiM, B. T. H. T. Baharudin, "Effect of fiber orientation on the structural response of a smart composite structure." Procedia Engineering Vol.50, pp.445-452, 2012.
12. E. J. Abdullah, D. L. Majid, F. I. Romli, Priyanka S. Gaikwad, L. G. Yuan and N. F. Harun. Active Control of Strain in a Composite Plate using Shape Memory Alloy Actuators. International Journal of Mechanics and Materials in Design, Vol. 11(1), pp.25-39, 2015.
13. Karl Johan Astrom and Tore Hagglund. (2005) Advanced PID Control. ISA-The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC 27709.
14. Ang K. H., Chong G. and Li Y. PID Control System Analysis, Design and Technology. IEEE Transactions on Control Systems Technology, 13(4):559-576, 2005.
15. Zhang D., Li H. and Collins E. G. "Digital Anti-windup PI Controllers for Variable-Speed Motor Drives using FPGA and Stochastic Theory," IEEE Transactions on Power Electronics, 21(5):1496 – 1501, 2006.
16. Bolton W. Mechatronics. Prentice Hall, 3rd Edition, Essex, England, 2003.