Design exploration study of a smart passive window based on NiTi bent actuator

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Abstract. This paper presents a multi-functional (sensing -actuating) greenhouse ventilation window design heated/cooled naturally by convection, to overcome different industry challenges in terms of designing smart applications. This ventilation window design includes a smart C-shaped NiTi actuator and three-pulley system, and all attached to the window. The force generated in the NiTi wire shrinks the C-shaped to open the ventilation window when the environmental temperature increases. When the environmental temperature decreases, the C-Shaped NiTi actuator returns to its initial position and closes the window. This smart actuation allows energy saving due to natural phase transformation induction (i.e. convection) and high force generation compared to the small NiTi wire mass. Using the pulley system is important as well to reduce the load on the NiTi actuator and enhance its long-life time. In this paper, the smart ventilation window actuator design has been discussed followed by a simulation study to investigate the NiTi C-shaped element behavior. The simulation results predict the thermomechanical behavior of the NiTi wire at the proposed greenhouse environmental conditions and the force generated in the wire. For future studies, an experimental investigation could be done to prove the simulation results.

1. Introduction
The smart systems design represents a new and potentially enormous opportunity to save energy, reduce noise and pollution, as well as improving the actuation performance [1]. The traditional greenhouse window openers available in the markets such as the electrical and the auto- drive window openers as shown in Figure 1 have very complicated work principles with high energy consumption and their dependences on artificial energy resources in addition to the many integrated components associated with the system such as temperature controller, remote temperature detector, auto-drive relay settings, pusher, rod and latches [2]. Therefore, developing NiTi SMA based actuators is important because of their large-strain capabilities and high force-to-weight ratios are widely used as compact, flexible actuators in a variety of industries. For example, NiTi SMA can be used as combination sensor-actuators in thermal bridges for cryogenic coolers, variable-area exhaust nozzles for turbomachinery, and active clearance controls for blade shrouds [3]. In this study, the main factor which may strongly affect or improve the thermomechanical behavior of the NiTi SMA actuator is the SMA element’s shape. The performance of the NiTi actuator depends mainly on the
mechanical design of the NiTi wire geometry [4]. Forms such as coil springs, for example, need more heat for activation due to the larger cross sections needed compared to wires with the same force output, but at greater ratio of element dimension and stroke. Additionally, inhomogeneous material stress in spring design leads to varying transformation temperature levels along the spring geometry [5]. So, a bent NiTi element subjected to bending force is considered in this study to allow moderate displacement capability at high forces, and homogeneous stresses which are suitable for our design application. In addition, the high surface area of the bent NiTi wire is another factor to ensure more heat exchange (accelerating the cooling process) with the environment. The smaller cross section of the bent NiTi wire compared with the spring ensures more energy saving.

![Figure 1. Natural ventilation window openers designs (a), Electric drive window opener (b), Auto-drive window opener [2].](image)

Slow actuation cycle due longer cooling time, and challenging motion control due to hysteresis, nonlinearities, and difficulties in measuring state variable such as temperature are the main challenging points in designing the NiTi SMA actuator [6]. However, in micro scale, a high frequency up to KHz could be achieved by the high convection-cooling rate and the resonance of the actuator [4]. In addition, the frequency could be improved when the heat treatment or the material composition changes the transition temperature [7].

The objective of this research is to study the design of an eco-friendly ventilation window based on a smart NiTi actuator. Implementing the thermomechanical model shows the ability of the designed “C-shaped” NiTi SMA wire to generate enough force to withstand against the window mass without generating a plastic deformation which leads to the “C-shaped” NiTi SMA’s failure. This design was built based on a certain limitation (i.e. strain limit 4%), prior design calculations and takes into consideration the ability of the “C-shaped” NiTi SMA to perform as an actuator and sensor at the same time using the simulation approach. The strain limitation was considered in this study based on the standard material properties database for design and reliability [8,9].

2. The Smart Ventilation Window Design
A schematic diagram of the proposed design of the “C shaped” NiTi SMA wire connected to a three pulley-system is illustrated in Figure 2. This Figure shows a three pulley-system named A,B and C and a rope connected to a 235.5 mm-long NiTi “C shaped” wire with the diameter of 1.5 mm from one side and to the window from the other side. The computational domain is a three-dimensional “C-shape” NiTi wire fixed from one end and stretched by the window mass form the other end surrounded by ambient air as shown in Figure 3.a.
Once the temperature inside the greenhouse rises from 22 ºC (<\(M_f\)) to 30 ºC (\(= A_s\)), the wire starts to shrink as shown in Figure 3.b and ends at 40 ºC (>\(A_f\)). Then, when the wire shrinks, it lifts the window up to allow air flowing inside the greenhouse to reduce the temperature inside. Then, once the temperature reaches 22 ºC inside the greenhouse, the wire starts to cool down to 22 ºC naturally by convection and stretch back to the initial state as shown in Figure 3.c and as a result the window starts to close down.

**Figure 2.** Smart window design based on NiTi SMA [10].

**Figure 3.** The “C-shaped” NiTi SMA wire during natural thermomechanical loading inside the greenhouse, (a) Initial state (deformation due to pulling up by window mass) at room temperature (b) The “C-shaped” NiTi wire original shape (shrinking due to temperature increase to above \(A_f\)) (c) Stretching back to the initial state by window mass due to cooling at room temperature [10].
3. The Design Variable’s Calculations

In this section, a “C-shaped” NiTi wire is proposed. This wire would be attached to the pulley system to actuate in two-way motion when heated (shrink) and cooled (relax) as shown previously in Figure 2 to allow the pulley system to open and close the window. The “C-shaped” NiTi wire shown in Figure 2 represents the mass $M_2$ from the right side which stand against the window mass $M_2$ from the left side as shown in Figure 4.a. The free body diagram which balance the tension force in the rope with the force gravity on the load shown in Figure 4.b for this type of triple pulley system provides a final mass equation as follows:

$$M_2 = 4M_1$$  \hspace{1cm} (1)

Equation (1) means the window mass is equal four time the wire mass or in other words, the force gravity that is being applied on the window is four times the force generated in the wire according to newton’s law ($F=mg$). In addition, to calculate the required linear displacement the pulley travels when pulling and lifting in each side (i.e. the “C-shaped” NiTi wire side and the window side), the work balance equation (force ($F$)×distance($D$)) was used as follows:

$$W_{out} = W_{in}$$  \hspace{1cm} (2)

$$F_2 \times D_2 = F_1 \times D_1 \rightarrow M_2 \times g \times D_2 = M_1 \times g \times D_1 \rightarrow M_2 \times D_2 = M_1 \times D_1$$

Since, $M_2 = 4M_1$, then

$$D_1 = 4D_2$$  \hspace{1cm} (3)

**Figure 4.** The tension force balance in the rope with the force gravity on the load (a), three pulley system with two masses assembly (b), the free body diagram of the whole assembly [10].
D1 represents the downward distance of the NiTi to raise M2 while D2 represents the upward distance of the window mass, M2, when being lifted. Using a pulley system in this ventilation window design based on NiTi actuator provides more ability of load reduction applied on the “C-shaped” NiTi wire. This will increase its lifetime and lead to increase in the number of thermomechanical cycles.

If the strain limit is restricted to 4% for life safety purposes for the NiTi wire, the bending radius (R) to 1.5 mm ‘C-shaped” NiTi wire diameter (d) as in equation (4) must be limited to approximately 15mm during heating and 75 mm during cooling the “C-shaped” NiTi wire as shown in Figure 5.

$$\varepsilon = \frac{d/2}{R}$$

(4)

From equation (4), we concluded that, the linear displacement the wire should displace down to lift each blade of the ventilation window, is 60 mm. Therefore, the relationship between the arc length (X) of the pulley and angular variables (R, θ) shown in Figure 6 when an object (rope) is rotating around a fixed axis (pulley axis) or rolling without slipping as follows:

$$X = R \theta$$

(5)

From equation (5), the radius of the pulley was calculated as follows:

Assume θ=90° then,

$$\theta (\text{rad}) = (\theta) \times \frac{\pi}{180} \rightarrow \theta(\text{rad}) = 90 \times \frac{\pi}{180} \rightarrow \theta(\text{rad}) = 1.57$$

$$R = \frac{X}{\theta} \rightarrow R = \frac{60}{1.57} \rightarrow R = 38\text{mm}$$

The ability of the “C-shape” NiTi to resist very large deformation when heated above austinite finish temperature due to the bent shape will increase the window blades opening angle which will improve the ventilation efficiency inside the greenhouse. The natural heating/cooling of the NiTi “C-shape” wire by
convection increases the energy saving and enhance the environmentally friendly designs. In addition, using the three-pulley system design increases the lifetime of the “C-shaped” NiTi wire by reducing the load applied on it and allow more weightlifting.

4. The design work principle
Detwinning the material under $M_f$ shown in Figure 7 followed by the heating with a high load ($>\sigma_s$) induces the reverse phase transformation to austenite as shown in Figure 6. Then cooling the material back to martensite will induce the forward transformation (detwinned martensite) again while the load is still applied. Similarly, loading the material mechanically above $\sigma_s$ in the austenite phase with a subsequent cooling to martensite will result in the formation of detwinned martensite and macrostructure shape change [11]. Heating the material back to austenite will result in full shape recovery in the presence of the load as shown in Figure 6. It should be noted that the phase transformation passes through new four transformation temperatures ($M_f^\alpha$, $M_f^\beta$, $A_s^\alpha$, $A_f^\alpha$) which highly depends on the load.

![Figure 7. Temperature induced phase transformation with loading [6].](image)

5. Simulation
Three-dimensional constitutive model proposed by Auricchio, which is already implemented in the built-in library of ANSYS Workbench 18.2, is used [1]. The proposed kinetic equations are implemented to simulate the “C-shaped” NiTi smart actuator using shape memory alloys based on phenomenological thermodynamic. The transformation phase diagram based on Auricchio is in micromechanical model. For more details about the constitutive model and the numerical implementation, refer to Alazzawi et al.[1,10]. The window design based on a NiTi actuator that behaves in a shape memory effect regime. The initial position of the NiTi wire at 22 °C is shown in Figure 3.a and it is in the martensite phase (closed status). When the temperature increases greater than 35°C Figure 3.b, the NiTi wire is in the austenite phase (open status). Then, when the temperature decreases to 22 °C, the wire will return to its original shape as shown in Figure 3.c. During the thermomechanical cycle from martensite to austenite, the window will continue to open and close depending on the increase and decrease in temperature naturally.

To achieve typical design conditions and costly effective, the academic FEA package Ansys workbench 18.2 was used and SME option is available in this version. The mechanical and thermal inputs properties were derived from [9,12,13] and simply insert in the engineering data table. The temperature-strain behavior of material in loading and heating cycles for the bending strain-state and thermal loading is defined by the
constants which shown in Table 1. The proposed boundary conditions, heating history are shown in Figure 8 and Figure 9, respectively. Static structural analysis system was selected first for calculating the force generated in the NiTi wire then thermal structural analysis was selected for developing the “C-shaped” NiTi SMA finite element model to describe a pre-stretched adiabatic and thermal conditions followed by heat applied in that adiabatic and thermal conditions.

| Property (unit)                        | Values  |
|---------------------------------------|---------|
| Elastic modulus of austenite (MPa)    | 51700   |
| Elastic modulus of martensite (MPa)   | 43,000  |
| Poisson’s ratio                       | 0.33    |
| Hardening parameter (MPa)             | 106     |
| Elastic limit (MPa)                   | 177     |
| Temperature scaling parameter (MPa.°C^{-1}) | 5.6     |
| Maximum strain (mm/mm)                | 0.04    |
| Thermal conductivity, (W/m. °C)       | 18      |
| Density, (kg.m^{-3})                  | 6450    |
| Loading temperature, °C               | 22      |
| Average heat capacity (J/kg. °C)      | 320     |
| Martensite finish temperatureMf (C)   | 22      |
| Martensite start temperatureMf (C)    | 25      |
| Austenite Start temperatureAe (C)     | 30      |
| Austenite finish temperatureAf (C)    | 35      |

**Figure 8.** The “C-shaped” NiTi wire load supports and boundary conditions during loading.
6. Results

After calculating the required variables to design the window in section 3, Ansys workbench 18.2 was used to calculate the force generated in the “C-shaped” NiTi wire when fixed at one end and displaced 60 mm from the other end using the structural analysis. The results showed that the force generated in the “C-shaped” NiTi wire, when is displaced 60 mm, is 1.3N. This generated force in the NiTi wire will be able to carry a 0.4 kg window mass. The next part of this study was investigating the thermomechanical behavior of the “C-shaped” NiTi wire during loading at 22 C and as shown in Figure 10.

**Figure 9.** Finite element solution steps (a), Displacement load steps and (b), Temperature load steps.
Figure 10. The temperature-strain behavior of “C-shaped” NiTi element during the first thermomechanical loading and strain recovery process.

7. Conclusion

In this study, a smart NiTi actuator is used to enable a greenhouse ventilation window heated/cooled by convection due to the environment’s temperature changes. The window design is simple and consists of “C-shaped” NiTi wire with three pulley system attached to window. A “C-shaped” NiTi wire in SME regime is used to close the window when the wire gets cold. In contrast, it is used to open the window when it gets hot. The shape memory behavior has been simulated using a pre-proven three-dimensional model which is implemented in Ansys 18.2. The results shown the accurate prediction of the thermomechanical behavior of the NiTi wire using finite element analysis. However, an experimental investigation needs to be done to prove the simulation results.

The proposed passive smart window design has unique features make it different from the traditional actuating system designs and as follows:

1. It is more efficient actuating system because it is more energy saving which depends on natural energy resources (i.e. thermal induction by convection from sun) which is a passive actuating energy and environmentally friendly.
2. Simple design components associated (i.e. pulleys, NiTi wire) which reduce the complexity of the system and lower the cost of fabrication.
3. This design is characterized by high force generation comparing to the device weight due to the unique properties of NiTi SMA which make it lighter weight than other actuating systems.
4. This design also allows moderate displacement capability due to the proposed “C-shape” which is higher than the straight NiTi wire displacement capability.
5. In addition, the simplified NiTi SMA actuator design will decrease the bulk and take less overall volume inside the greenhouse.
6. A three-pulley system associated with the design also adds another advantage to it through more weightlifting and overall loading reduction on the NiTi SMA, which increases its lifetime.
7. A multi-functional usage due to the temperature sensing and mechanical actuation ability at the same time.
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