Technical Note

Development of a proof-of-concept aircraft smart control system

P. Hutapea
hutapea@temple.edu
K. Jacobs, M. Harper, E. Meyer and B. Roth
Department of Mechanical Engineering
Temple University
Philadelphia
Pennsylvania, USA

ABSTRACT

Hutapea *et al*[1] showed that an actuation system based on shape memory alloy coils could be employed for a wing flap of an aircraft. A continued research and development of these previously demonstrated smart flight control mechanisms was performed with the goal to develop a proof-of-concept shape memory alloy (SMA) actuation system, which utilises SMA springs to control the six degrees of freedom of an aircraft. For this actuation system, the springs are heated via an electric current, causing the spring to contract as the metal's phase changes from martensite to austenite[2–5]. The contraction allows the springs to function as linear actuators for the aircraft's control surfaces, specifically the flaps and ailerons on the wings and horizontal stabilisers and a rudder on the tail. As a significant advancement to the overall actuation system, an air burst-cooling system increases the cooling rate of the coils by means of forced convection. Computer-based finite element model analysis and experimental testing were used to define and optimise SMA spring specifications for each individual control surface design. A one-sixth scale proof-of-concept model of a Piper PA-28 Cherokee 160 aircraft was constructed to demonstrate and to verify the final actuation system design.

RESULTS AND DISCUSSION

Shape memory alloys (SMA) are 'smart' materials that change shape when heat or electric current are applied. There have been many aerospace applications of SMA as discussed in a review by Hartl and Lagoudas[6]. Some examples of conceptual aviation applications of SMA include the Smart Wing program and the Smart Aircraft and Marine Propulsion System Demonstration (SAMPSON)[7,8], smart wing control effectors[9], active wing design[10], and in-flight tracking

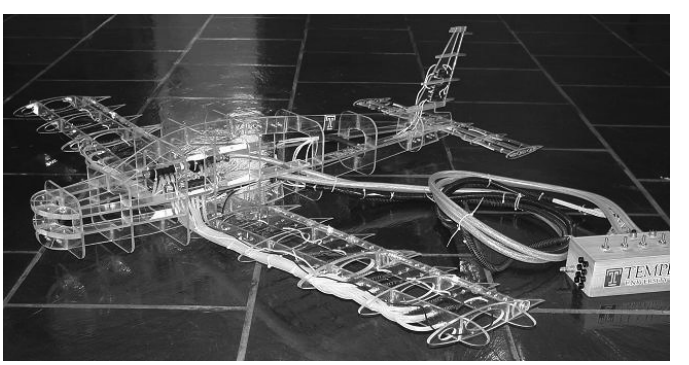


Figure 1. The developed 'Proof of Concept' model

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of helicopter rotor blades[11]. A flight control system that uses SMA is not only achievable, but also lighter than its hydraulic counterpart. A successful design will result in system functionality as well as higher fuel efficiency.

Finite element modeling using SolidWorks/FloWorks[12] was employed to analyse the magnitude of the force that the SMA will have to overcome during all stages of flight. Separate computational domains were created for each actuation surface solid in order to allow for individual precision in the surface's boundary layer mesh. Scaled test parameters such as take-off and maneuvering speed were defined to be equivalent to that of the limitations of the available wind tunnel to test each element's system. Fluid mechanic analysis was performed to calculate the forces of each mechanical control surface. The pressure data was integrated both on the top and the bottom of the actuation surface to calculate the resultant pressure at the centroid of each control. The resultant pressure was used to identify the stages of flight in which the peak forces would be acting on each controlling unit and based our aircraft's entire operational range off of these forces. Necessary actuator forces were calculated using static analysis where the necessary torque is equal to the product of the force from pressure and the distance from the center of the flap hinge. The required force is equal to the torque divided by the radius of the flap hinge. The force from pressure is the integral of the pressure over the flap of the wing applied at the centroid of the flap.

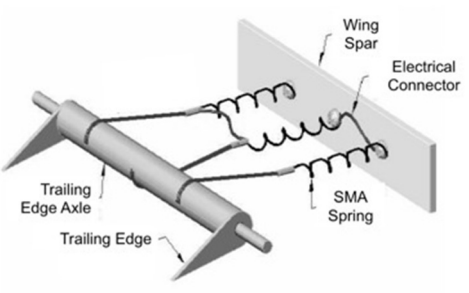
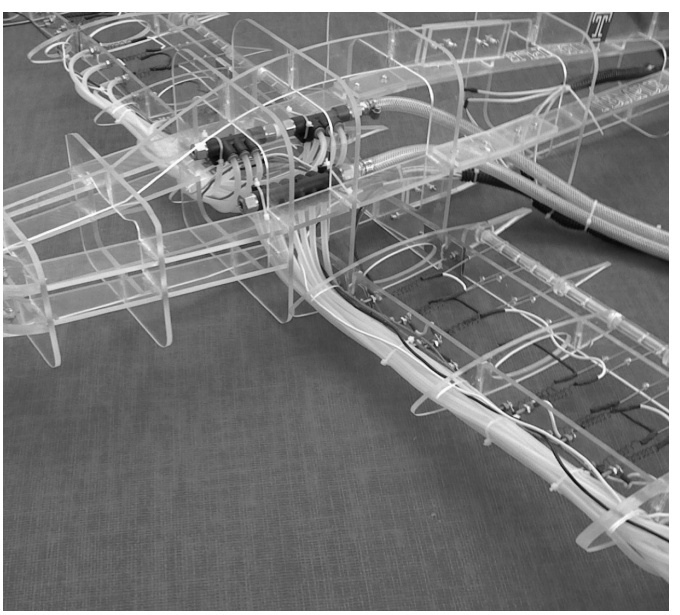


Figure 2. The dual-sided configuration.

The design of our SMA-controlled actuation system is based on a dual-sided configuration (Fig. 2). This system creates the needed actuation by switching between two layers of SMA springs. The upper layer of SMA springs is attached tangentially to the top of the control surface rotation rod. When a current is applied through these springs, the SMA contract and the control surface rotates upward. Similarly, the lower layer of SMA springs is attached tangentially to the bottom of the control surface rod. When a current is applied to these springs, the SMA contract and the control surface rotates downward, creating the necessary deflection. The ability of SMA to change its crystallographic structure is directly related to the temperature changes[2–5]. During experiments, SMA temperatures varied between 22°C (ambient temperature) to 160°C. This high temperature extreme was not employed in the design of our actuation system as the SMA can achieve a plausible amount of work at a lower temperature; a successful actuation cycle was accomplished in a few seconds with SMA temperatures reaching 40°C to 65°C. The prototype structures used the rib and spar structures; this best suited our application because the space within the wing structure allowed room for the necessary wiring and mechanical applications (Fig. 3). The fuselage was designed to support the wing and tail boxes as well as be able to accommodate extra cooling equipment that could not be contained in the wings (Fig. 3). The data collected through the modeling process along with basic experimental testing determined the number, shape, and size of SMA actuators needed for each individual control surface.

The electrical current running through the SMA was clearly capable of elevating temperatures in a relatively small amount of time. However, once the current was stopped, heat transfer out of the spring was solely dependent on free convection to the ambient. Most importantly, a spring that remains hot enough to stay austenitic will be resistive to countermotion from other springs[1]. This process was observed to be much more time consuming than the initial heating. The most important aspect of this observation was that the SMA remained in a mostly contracted state as long as temperatures were high enough to support its phase change[13,14]. It was noted that while the spring remained in a contracted state, it provided higher resistance to the actuation of the spring countering its motion.

In solving this issue, a cooling system was added to the basic smart actuation design. This system introduces bursts of high velocity air to cool SMA springs quickly (Fig. 4(a)). This system increases the heat transfer out of the springs by introducing forced convection. It was observed that the SMA could be cooled from approximately 65°C to ambient in a matter of seconds. Additionally, SMA spring subjected to both electrical current and forced convection could complete an actuation cycle virtually unaffected



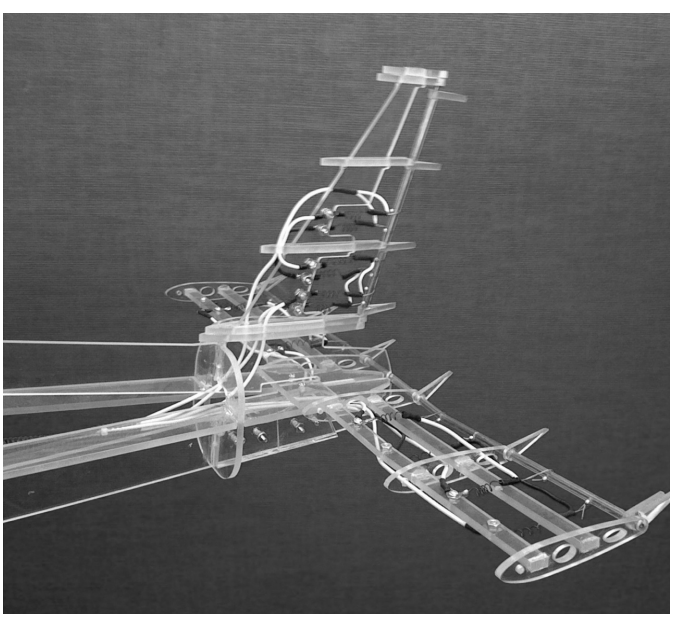
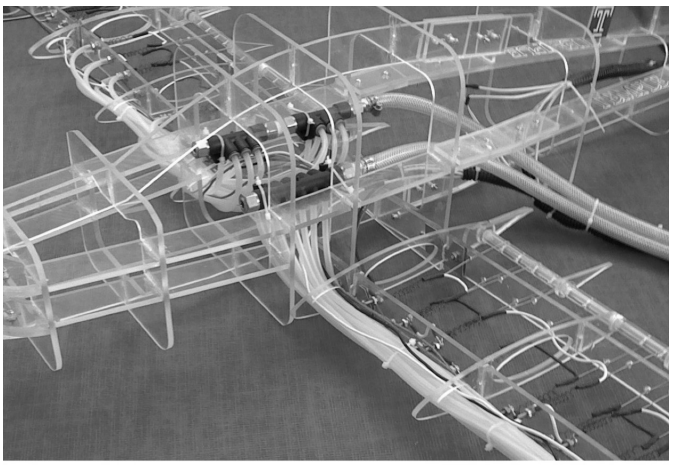
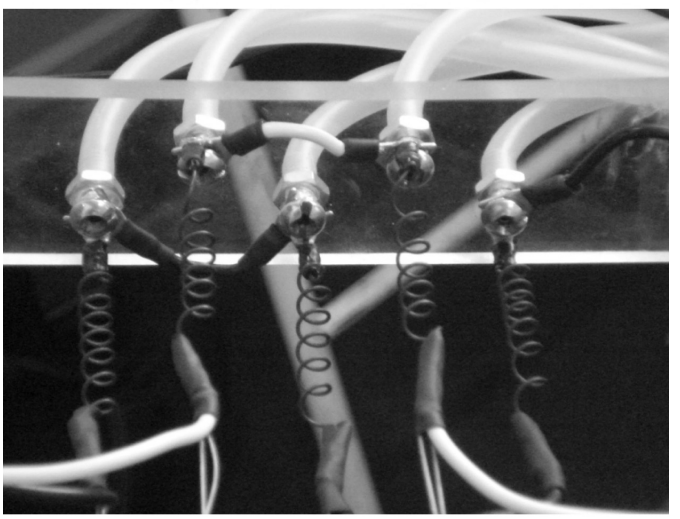


Figure 3. A wing box (left), a rudder and a stabiliser (right)

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(a) Inside the fuselage



(b) Vented screws

Figure 4. A cooling system.

and this should reduce material hysteresis and fatigue[6,13,14]. In this design, the moving air came from a compressed supply, which traveled through a network of tubes before passing through a vented screw mounted with the SMA spring. The SMA were mounted in these sections using vented screws which were created by drilling directly down the length of the screw with a milling machine and adjustable chuck (Figure 4(b)). Quarter inch tubing was then attached to the threaded end of the screw to provide air bursts down the length of the heated SMA springs. The other end of the tubing was connected to two manifolds, which evenly distribute high velocity air from an external compressed air tank to the SMA springs, located in the fuselage of the model aircraft. The forced convection cooling system almost instantaneously cooled (in approximately 2 seconds) the SMA springs past their transformation temperature (Fig. 5). As a result, faster actuation was observed through testing of the model itself while using this more optimised cooling mechanism. For an actual plane in flight, a compressed air supply can facilitate this type of convection, or a more creative design can utilise the fast-moving air around the plane as an air source.

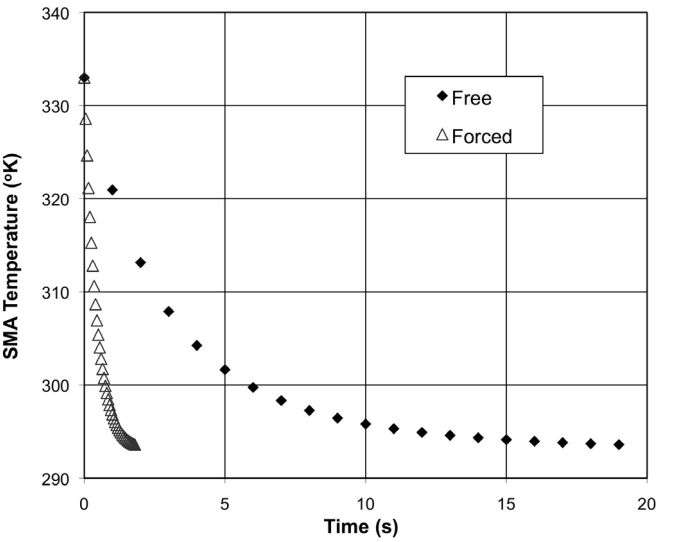


Figure 5: Free and forced convection cooling curves.

SUMMARY

It has been shown that the surface control of the prototype could be actuated utilising the SMA springs. The proposed cooling system was developed to accelerate the SMA recovery and the actuation and limit the overheating of the SMA actuators. In addition, controllable SMA actuator temperature is necessary to reduce material hysteresis and fatigue. The following are suggestions for future work on enhancing the SMA actuation system and enable the eventual creation of a full size 'smart' plane: (a) The implementation of a gear and pulley system would be an excellent modification for future designs (Figure 6). Utilising gears and pulleys would allow for the system to be centralised to the fuselage of aircraft, enhancing both the mechanics of the plane as well as routine maintenance. There are many advantages to this new system. It would permit the use of transmission mechanisms, including a clutch and brake. These modifications would increase sensitivity and adjustability while decreasing vibration within the control surface. In the new centralised system, the work would be performed in a small portion of the fuselage of the aircraft and would be transferred through any of a variety of power transmission components such as gears, shafts and pulleys. (b) Another hope for the future of a 'smart' plane includes the design of a flight-worthy model aircraft. An optimal flight control system for this model will require the use of a feedback control system. This system will need to monitor the physical position of each control surface as well as the electrical status through each spring set. Information can be relayed back to a processor, which can increase or reduce current, apply a brake, or even supply an air burst to ensure that the control surface is performing an expected function.

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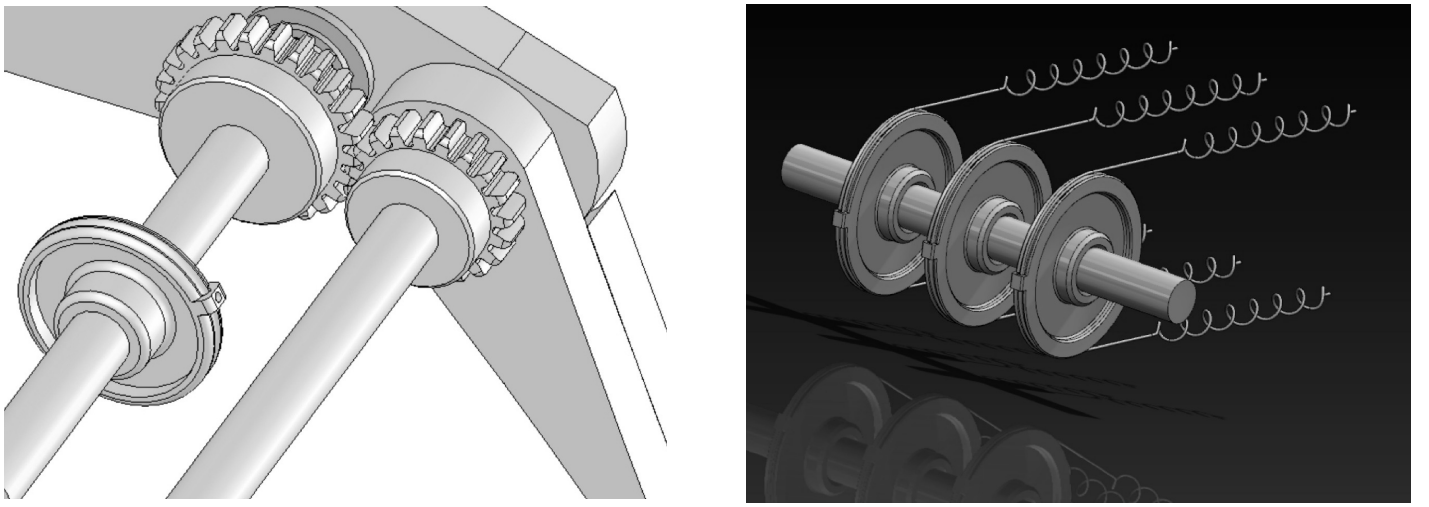


Figure 6. Illustration of the proposed gear and pulley system.

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