Aircraft Engineering and Aerospace Technology
Emerald Article: Development of a smart wing
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Article information:
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Development of a smart wing
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Abstract
Purpose – The objective of this paper is to develop an actuation system utilizing smart materials such as shape memory alloys (SMA) to control the position of an aircraft’s flaps.
Design/methodology/approach – The proposed smart wing consisted of SMA springs that were fixed at one end to the wing box toward the leading edge of the airfoil. The other end of each spring was attached tangentially to a rotating cylinder fixed to the flap. The springs were arranged in an upper and a lower layer to cause rotation of the flap in both the upward and downward directions. The spring actuators were controlled by the introduction of heat resulting from the applied current. A prototype of the smart wing was developed and tested to demonstrate the design concept.
Findings – A prototype of a smart actuation system for controlling the flaps of an aircraft was successfully developed. Through the experimental and theoretical analyses conducted, the design was validated and showed strong potential for future application.
Practical implications – The proposed concept can be applied to other aircraft systems such as ailerons, slats, rudders and elevators.
Originality/value – The prototype of a smart wing is unique. It utilizes smart materials for aircraft flap actuation. The concept can be applied on ailerons, slats, rudders and elevators.

Keywords Alloys, Aerospace engineering, Aircraft, Physical properties of materials

Introduction
The objective of this work is to develop a smart actuation system utilizing shape memory alloys (SMA) to control the position of aircraft’s flaps. SMA materials are metallic alloys that can undergo martensitic transformations as a result of applied thermo-mechanical loads. The alloys are capable of recovering plastic strains when heated above a certain temperature (Waram, 1993; Patoor et al., 2004; Nishiyama, 1978). SMA are capable of achieving several different phases through thermal- and stress-induced loads. The two primary phases of SMA are martensitic and austenitic. The austenitic phase is the high-temperature state of SMA. The martensitic state occurs at lower temperatures and is achieved by rapid cooling from the austenitic state – this rapid cooling or quenching results in the formation of a precipitate. In this transformation, the cells of the material change from a perfect face-centered cubic shape in the austenitic phase to a distorted body-centered tetragonal shape that is no longer symmetric.

The most commonly used SMA is a nickel-titanium alloy to which copper is occasionally added to aid in the strain recovery process. The process of creating movement (or shape change) is based on a five-step procedure that takes place within the material. These five steps compose one of the most important characteristics of SMA – the shape memory effect. The first step of the transformation takes place at a high temperature with zero stress and strain; this is what is referred to as the parent austenitic phase. Next, the parent austenitic structure is cooled in the absence of both stress and strain to create twinned martensite. As the material is cooled, a precipitate is formed between the grains of the metal. Then, the material is stressed to reverse the twinning process from the diffusionless phase transformation. This phase change develops inelastic strains within the now detwinned martensite. The load is then released but the material still retains its detwinned form with the inelastic strains. Finally, the SMA is then heated to its parent austenitic start temperature and all inelastic strains are recovered, thereby returning the material to its original shape and composition. The entire process is shown by Figure 1 (Nishiyama, 1978; Kaufman and Cohen, 1958). Other behaviors of SMA that must be considered for our wing design are one-way shape memory effect, two-way shape memory effect, hysteresis and material training (Waram, 1993; Huang and Toh, 2000; Huang and Goh, 2001).

The properties of SMA make them of special interest to those in the aerospace field. In aircraft design, the generation of lift is the most crucial aspect of flight. All standard aircraft employ fixed geometry wings. A fixed geometry wing is one whose design has been optimized for a specific flight purpose; the wing shape of a Boeing 747 is vastly different from that of an F-18A due to different lift and drag requirements. The trailing edge of an airfoil in particular has a considerable effect on the lift generated by a wing. Devices such as flaps are capable of greatly increasing a wing’s lift during different flight conditions. Flap systems and other flight control devices could be optimally controlled by SMA actuation. SMA actuators can be designed to be lightweight, high-strength, large-deflection, quick-response and impervious to electromagnetic pulses.

Owing to strong industry competition, aircraft technology is constantly improving and efficiency is highly valued. Transonic fixed geometry wings (for flight in the velocity range around the speed of sound, approximately Mach 0.8 to 1.3) of civil aircraft show much room for improvement. Such fixed geometry wings are optimized for only one design point or flight condition, characterized by parameters of altitude, Mach number and aircraft weight.

As aerodynamic investigations have shown, one possibility to compensate for this major disadvantage lies in the chord wise and span wise differential variation of the wing camber...
for mission duration (Monner et al., 2000). Wing camber variation is envisioned to be used for the replacement or enhancement of a given flap system. The design of a flexible flap system for an adaptive wing could be widely used in civil transport aircraft that would allow for both chord- and span-wise differential camber variation during flight. Since both lower and upper skins could be flexed by active ribs, the camber variation could be achieved with a smooth contour and without any additional gaps.

It would be very beneficial to use aircraft with wings capable of chord- and span-wise differential camber variation. The profile of a camber-varying wing would be able to adapt in-flight to different aerodynamic and geometric requirements resulting in better flight control and optimized lift generation. The cambering system could also be built such that during its actuation the structural stiffness of the wing would not change. Chord- and span-wise differential camber variation offer significant improvements to aerodynamics and structural efficiency. Possible benefits include:

- optimized lift/drag ratios and higher aerodynamic efficiencies resulting in extended cruising range and reduced fuel consumption;
- improved operational flexibility by setting lift/drag ratio to higher values;
- noticeable reductions in structural weight; and
- financial savings in development costs.

Attempts have been made by others in the scientific community to use SMA actuation to control the trailing edge of a wing. One group of researchers embedded SMA wires into a NACA 0012 helicopter rotor airfoil section with a 0.305 m chord adjoined to a trailing-edge tab with a 0.1 m span and a 0.06 m chord. The actuator consisted of a wire clamp, a hinge tube and several pre-strained 0.3 mm diameter SMA wires. The SMA wires had a 3.16 per cent initial pre-strain, and the system resulted in a tab deflection of 29° (Epps and Chopra, 1999).

Owing to their drastic impact on the lift and drag ratios of a wing, flaps are nearly indispensable in modern aircraft design. One of the greatest advantages of using shape memory actuation to control an aircraft’s flaps would be the lightweight design that would effectually allow for greater fuel efficiency. Additionally, SMA actuation offers variable-force control and impressive elongation and recovery distances of the actuator mechanism. A successfully designed SMA flap actuation system would also require low maintenance if implemented due to the small number of moving parts, and the system could be installed at relatively low cost (negligible cost beyond the price of the SMA material). If successful, this shape memory flap actuation system could also be easily applied to other aircraft flight control systems and high-lift devices, including an aircraft’s slats, rudder, elevators, or ailerons.

In our design, actuation of the trailing edge of the wing was achieved through the shape memory effect. Figure 2 shows the design concept of the tab actuator, which consisted of an upper and lower set of SMA springs, fixed at one end and connected to a hinge tube at the other to actuate the tab. Both sets of springs had the same initial length, initial plastic deformation and cross sectional area. To deflect the tab upward, the upper springs were heated while the lower springs remained at ambient temperature. The force produced from the contracting SMA spring caused a counterclockwise moment about the hinge tube’s axis, which rotated the hinge tube and caused deflection of the tab upward. Deflection of the flap in the downward direction occurred if the lower springs were heated while the top springs remained at ambient temperature. The force produced from the actuation of the lower set of SMA springs caused a clockwise rotation of the hinge tube, as shown in Figure 2.

The following two sections discuss our design methods through performed analysis and experiments and prototype tests to evaluate the feasibility of our smart wing prototype.

### Design methods: analysis and experiment

Our design consisted of a portion of an airfoil with flaps controlled by SMA actuation. The flaps were rigidly fixed to a rotating tube to which the SMA springs were attached. The other end of each SMA spring was fixed to the front of the wing box. In our model, four SMA springs comprised the upper layer of springs that were attached tangentially to the top of the flap tube. Similarly, the bottom layer of four SMA springs was attached tangentially to the bottom of the flap tube. When current was directed through the upper layer of springs, the SMA spring actuators would contract to raise the flaps. Likewise, the direction of current through the bottom layer of springs resulted in a downward deflection of the flaps. A simplified illustration our final design is shown in Figure 2.

In the illustration, the upper contracting springs represent the springs heated from the application of current. Figure 3 shows the actuation of the trailing edge of the wing was achieved through the shape memory effect. Figure 2 shows the design concept of the tab actuator, which consisted of an upper and lower set of SMA springs, fixed at one end and connected to a hinge tube at the other to actuate the tab. Both sets of springs had the same initial length, initial plastic deformation and cross sectional area. To deflect the tab upward, the upper springs were heated while the lower springs remained at ambient temperature. The force produced from the contracting SMA spring caused a counterclockwise moment about the hinge tube’s axis, which rotated the hinge tube and caused deflection of the tab upward. Deflection of the flap in the downward direction occurred if the lower springs were heated while the top springs remained at ambient temperature. The force produced from the actuation of the lower set of SMA springs caused a clockwise rotation of the hinge tube, as shown in Figure 2.

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the manufactured prototype of the flap using NACA 2412 airfoil. There are two critical design considerations that were used to evaluate the feasibility of the smart actuation system. These are SMA material response time to heating and maximum force on the flap during a simulated flight.

**SMA material response time to heating**

Response times of the model were sufficiently quick; on average, full deflection either upwards or downwards could be achieved 3 s after the application of current through the desired layer of springs. Each layer of springs was wired in a series circuit and powered by a voltage generator. Experimentally determined electrical properties of each SMA spring used in the prototype are 0.5 Ohms, 3.40 A and 1.70 V. The electrical power was controlled by a three-way switch that provided three possible settings: current delivery through the upper layer of springs (flap deflection up), current delivery through the lower layer of springs (flap deflection down), or no current supplied (power off/standby). It was possible to activate either layer of springs by changing the activation temperature for the material. To gather the experimental data represented by the solid line curve in Figure 4, the same voltage and current applied to each spring in the prototype were applied to the single SMA spring in the trial. A thermocouple was used to take temperature readings while the spring was being heated, and the data were collected from video analysis of the experiment. Quantitatively, we found it possible to predict the temperature change of the SMA spring in different situations using heat transfer correlations. Assuming the spring to be a cylinder in calculations and taking the SMA material properties from information contained in journal articles, it was possible predict the heating trend for the spring. The lumped capacitance assumption was validated and employed for this calculation, and the temperature distribution throughout the material was taken to be uniform. With these validated assumptions, we were able to calculate and predict the SMA temperature over time for a given current. As mentioned above, the solid line curve in Figure 4 shows the spring temperature measured in the experimental trial, while the dashed line curve represents the temperature calculated from the heat transfer correlations. The spring for this experiment was cylindrical with a diameter of 0.2 mm and a length of 9 mm. Material properties of the SMA spring were commonly obtained from literatures and manufacturer’s data. The equation is listed below (Incropera and DeWitt, 2001):

\[ T = \frac{I^2 R L}{h A} (1 - e^{-\frac{h A t}{\rho V}}) + T_\infty \]  

where \( T \) is the estimated temperature; \( I \) is the applied current, 3.6 A; \( R \) is the spring resistance, 0.5 \( \Omega \); \( V \) is the spring volume; \( \rho \) is the spring density, 6,450 kg/m\(^3\); \( h \) is the convection coefficient, 35 W/(m\(^2\) K); \( c \) is the specific heat, 322.38 J/(kg K); \( A \) is the spring surface area; \( T_j \) is the surface temperature, 323 K; \( T_\infty \) is ambient temperature, 303 K; and \( t \) is the time.

Cooling from activation temperature to room temperature under free convection conditions was also analyzed, as shown in Figure 5. Similar to the heating analysis, the solid line curve in Figure 5 shows the experimental data obtained from video analysis. The dashed line curve represents the data obtained from numerical calculations. In the calculations, all the energy stored in the springs from the heating by the electrical current is dissipated to the ambient. The equation used to predict cooling temperature of the SMA spring is reproduced below. The cylindrical shape of the spring was assumed again to derive the cooling equation. The equation is given below (Epps and Chopra, 1999):

\[ T = (T_j - T_\infty)e^{-\frac{h A t}{\rho V c}} + T_\infty \]
As is made clear by Figures 4 and 5, the experimental data and theoretically obtained data closely match. From the theoretical calculations, we are capable of predicting the behavior of the SMA material accurately. Using the correlations, we were able to predict the heating trend for the SMA spring at different levels of current.

From the analysis and comparison of two heating trials, we were able to confirm that the delivery of a greater electrical power to the SMA spring results in a more rapid heating of the material and shorter response time. The initial spring temperature was set to be 275 °K to represent the temperature at a cruising altitude of approximately 3,700 m. We were then able to calculate the voltage required to bring the material to a certain optimal temperature. Optimally, the spring should be heated to activation rapidly without bringing the material temperature excessively high so as to prolong the cooling time. For the theoretical analyses, two cases are considered. The first case, lower current, used 0.5 Ωs, 7.2 A, 3.6 V. The second case used 0.5 Ωs, 8.0 A and 4 V. Figure 6 shows the heating of the SMA spring using the two different levels of current and voltage. In the graph, the solid line curve represents heating by a current of 8 A while the dashed line curve represents heating by a current of 7.2 A. As shown in Figure 6, a relatively small increase in power delivered to the spring results in a significant reduction in activation (heating) time. This theoretical analysis served to illustrate the impact of electrical power on the SMA spring activation time, and also explored the performance of our model exposed to realistic flight temperatures.

**Figure 6** Temperature profiles for two different loading conditions

![Temperature profiles for two different loading conditions](image)

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before cruising was determined to be 19 per cent by integration. Again, the pressure at the leading edge is at the left of the graph and the pressure at the trailing edge is at the right of the graph.

Using the above pressure distribution ratios of 25 and 19 per cent corresponding to the two different critical instants of flight, we were able to predict the minimum force required to actuate the flap. The force values of 6.4 and 4.94 N were determined, respectively, by taking 25 and 19 per cent of the total maximum force applied to the wing of 26 N. Of these two force values, clearly 6.4 N is the greater value which we took to be the minimum required force that our flap system must generate. The following prototype tests would show the performance of manufactured prototype compared to the predicted required conditions.

**Prototype tests**

Following the completion of our final prototype model, numerous tests were conducted to evaluate its performance. As shown in Figure 9, a force gauge was used to measure the maximum upward force generated by the rotating flaps. Although each SMA spring is capable of contracting with more than 10 N of force, some mechanical energy is lost in the rotational system. The four springs together in the top spring layer were capable of raising the flap with a maximum force of approximately 30 N at the base of rotation and 5 N at the trailing edge. Thus, the average force generated by the flap actuation system was 17.5 N, which exceeded our minimum force requirement of 6.4 N.

Additional tests of the design were performed using the wind tunnel in the Temple University fluids laboratory. Since the relatively large size of the prototype prevented testing inside the
actual tunnel, the test was conducted at the tunnel outlet. A mounting bracket was created to hold the wing securely in place at a fixed position during aerodynamic loading. Testing our prototype at the maximum wind tunnel air velocity of 21.3 m/s, we were able to evaluate the performance of our design under dynamic loading conditions. The SMA actuators were able to control the position of the flap successfully, with minimal additional time delay due to the dynamic loading. The time required for the flap to go from maximum deflection in one direction to maximum deflection in the other (either raised position to lowered or vice versa) was approximately 6 s. Even testing the wing at approximately one-third of the air speed of ideal testing conditions, significant lift generation was observed. When the flap was fully deflected downward, the wing itself started to slightly rotate upward at its anchored point. This test validated our design concept under low-airspeed conditions and indicated that the displacement of the trailing edge of an airfoil contributes greatly to the generation of lift. The wind tunnel experiment is shown in Figure 10.

Figure 10 Testing the flap actuation system at a wind tunnel velocity of 21.3 m/s

Conclusions

A prototype of a smart actuation system for controlling the flaps of an aircraft was successfully developed. Through the experimental and theoretical analyses we conducted, our design was validated and showed strong potential for future application. The goals of on-going studies are to develop a control system, to further analyze in-flight dynamic loading conditions, and to apply the design to other aircraft systems such as ailerons, slats, rudders and elevators.

References


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