PERSPECTIVES FOR A SMA ACTUATED WING STRUCTURE AIMING AT GLOBAL TWISTING CONTROL

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Nowadays, electrical actuators are widespreading in aeronautical applications with the development of the "more electric" aircraft concept. Nevertheless, classical electromagnetic actuators are not the only technologies of interest in this field.

Thanks to new electroactive materials, a significant wing-scale activation of the airfoil may indeed be considered. In this context, collaboration between Airbus and the electrodynamics – EM3 research group of INPT/ENSEEIHT/LEEI was carried out, so as to study the opportunity of achieving an active twisting control of a wing based on these materials.

First of all, a panel of available materials is proposed. After having defined the actual requirements for airfoil optimization, this paper illustrates the potential of electroactive materials either for quasi-static or frequential operating.

Then, the results of a feasibility study considering a shape memory alloys actuation are presented. This study deals with the results of the calculations in terms of mass, energy and power requirements.

To conclude on the feasibility of the defined actuation concept, an experimental study is presented. Firstly, a high strain / stress linear actuator based on Shape Memory Alloys (SMA) is presented. Then a small scale wing model actuated by SMA wires is described.

Active wing: classification of the requirements

The control surfaces may be sorted into three classes, depending on their dynamics :

- low-speed control (global behaviour control of the aircraft in quasi-static)
- high-speed/strokes control (aircraft displacements within a few seconds)
- high-frequency actuation (vibratory and aerodynamic phenomenons control)

Thanks to electroactive materials, it is possible to define new structures of distributed actuators. Even though the design of high-speed/strokes actuators seems to be presently out of the range of these materials because high stresses and displacements are both required, these technologies may be suitable for quasi-static and dynamic shape control.

Dynamic vs. quasi-static shape actuation

Because of the variations of the in-flight conditions, the optimal airfoil shape leading to the best lift/drag ratio may vary. Therefore, the design of an adaptive wing may be suitable to reduce the power consumption of the aircraft (camber adaptation for example).

Until now, two possibilities were mainly studied:

- global wing shape control (camber and twist control, cf. [1] and [3])
- trailing edge deflection control (cf.[2])

Another opportunity given by distributed electroactive actuators is the frequential control of the airfoil surface. The aim may be the reduction of parasite vibrations (helicopter rotor) or the control of air flows close to the surface (turbulent air drag reduction).

Panel of available electroactive materials

Electroactive materials make it possible to achieve integrated actuators with especially significant power and energy density compared to classical electric actuators using electromagnetic effects.

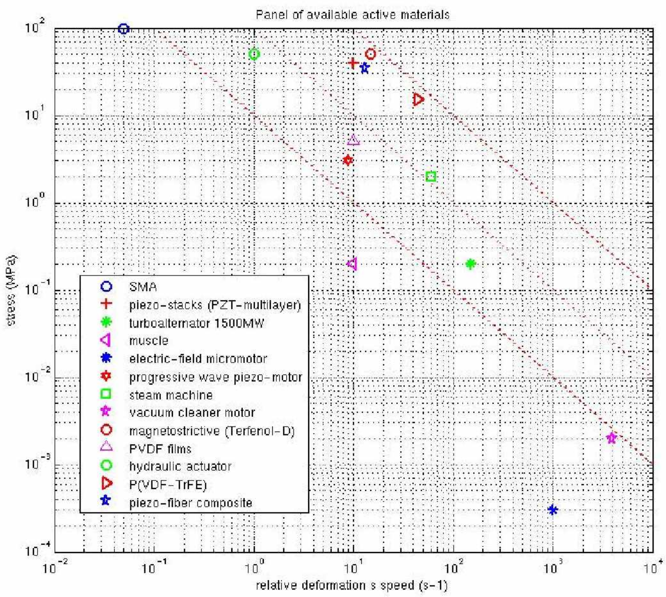

Fig. 1

For the moment, the most widely used materials are piezoelectric ceramics (1500 ppm max, 30 MPa max, up to 100 kHz) due to their ability to achieve a high power density electromechanical energy conversion.

For quasi-static applications, Shape Memory Alloys (SMA) seem to be extremely promising (5% strains when heated, under stress up to 100 MPa).

The main limiting factor is the frequency range: the thermo-mechanical coupling forbids high-frequency actuation.

Fundamentals of shape memory effect

Shape Memory Alloys are materials with specific thermo-mechanical coupling properties. When cold, these alloys may be easily deformed. But after heating, they tend to return to their original shape.

These properties are due to the existence of two different phases within the crystalline structure: a low-temperature (martensite) and a high-temperature phase (austenite). The martensite structure is made of several variants and when submitted to external forces, it aligns with stress. A global deformation with large amplitude can thus be observed.

When the mechanical stress is withdrawn, residual strain remains which disappears after heating. A classical stress / strain curve is plotted in Fig. 2.

The observed stress and strain during heating are to the order of 100 MPa and 5%. The SMA's behaviour depending on temperature is strongly hysteretic, as shown in Fig. 3.

The shape memory effect is exhibited by many different metallic alloys. Nevertheless the most commonly available SMA are Ni-Ti alloys, known as nitinol.

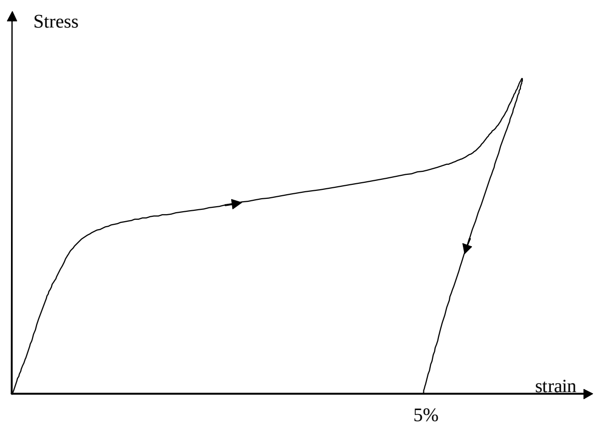

Fig. 2

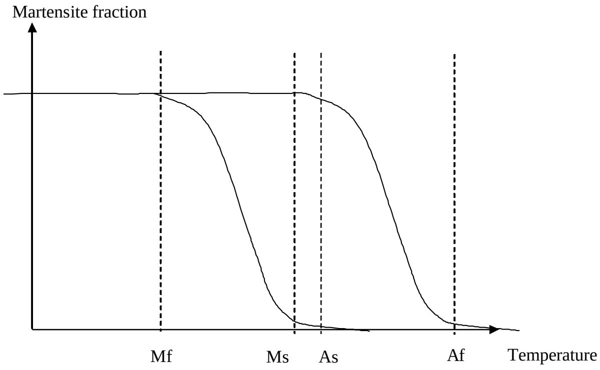

Fig. 3

Mechanical and energetic requirements of the desired actuation

Description of the reference structure

The studied structure was defined in collaboration with Airbus France (flight control actuation Dpt. – D. Van den Bossche). It is based on the real wing structure of the recently designed A380 airplane.

Since the required wing twist is to be measured at wing tip, it was decided to localize the actuation close to the tip, on the 10 last wing boxes.

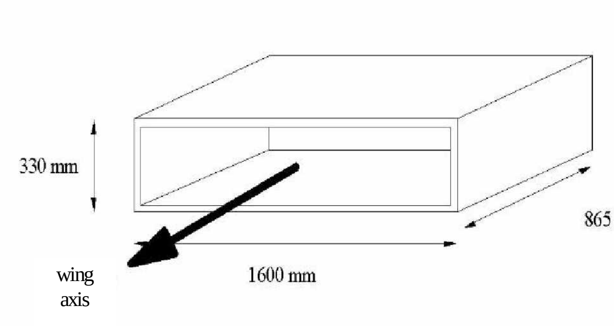

Fig. 4

The computations are done considering the reference box shown in Fig. 4, whose dimensions are consistent with those of the airfoil structure at wing tip.

Actuation strategy

So as to achieve the desired 1° twisting at wing tip, different actuation strategies may be considered (cf. Fig.5):

- actuation by a torsion tube (1)
- actuation by wires along the wing axis (2)
- actuation by wires along the box diagonal (3)

Each wing box is actuated separately, and the global wing tip twist is therefore the sum of the resulting deformations.

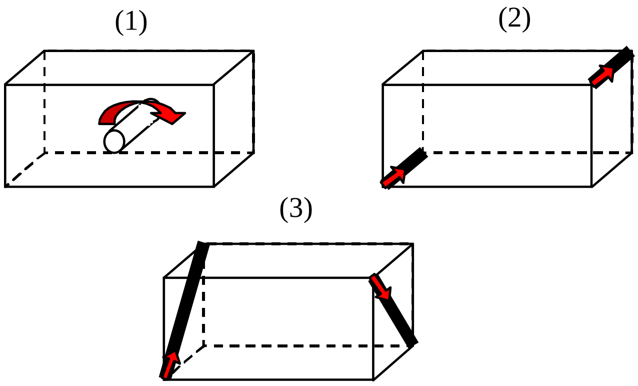

Fig. 5

To obtain a 0.1° twisting of the reference box, the required forces are those given by Tab. 1, according to the results of the performed FEM-software ANSYS simulations.

Table 1

Actuation mode	Required force	Total strain energy
1	$4.7\ 10^{4}$ N	63.4 J
2	$4.8\ 10^{5}$ N	1553 J
3	$1.76\ 10^{5}$ N	241 J

Therefore, among these actuation modes, only two occur to be of interest for the studied application. The wire actuation along wing axis seems indeed to be avoided, since its efficiency is very bad in terms of energy.

At first sight, the actuation by a torsion tube occurs to be especially relevant for twisting control. Nevertheless, the adding of such a significant mass as a torsion tube may dramatically increase the mass of the final actuation device. That is why this study focuses on a diagonal wire actuation of the wing box.

Evaluation of the requirements

To define the amount of active material required by the function, an estimation of the needed forces and strains on each wing box has to be made.

With the forces reported in Table 2, the achievable deformation of wing is reported in Fig. 6. Simulation is based on ANSYS.

If an admissible stress of 100 MPa is considered for SMA wire, with a typical strain of about 5%, then the required mass of active material is 50 kg for the whole airfoil structure.

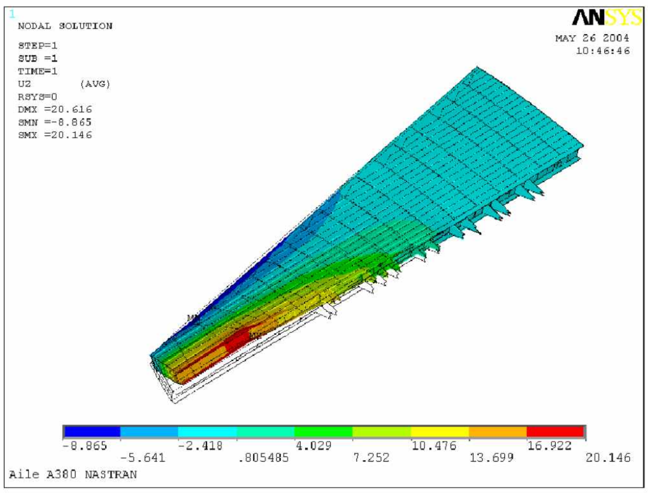

Fig. 6

The low needed mass tends therefore to demonstrate the relevance of the considered actuation concept.

The phase-change heat of nitinol is to the order of 20 $kJ.kg^{-1}$. Thus, the energy required by the austenitic transformation itself is about 1MJ. If the associated heating is considered, then the required energy may be to the order of 3MJ with an austenite-finish temperature 50 K upper than the ambient temperature.

Table 2

Required forces and displacements according to ANSYS simulations (10 wing boxes actuated)

Applied forces (10^5 N)	SMA wire displacement (mm)
3.71	2.8
3.54	2.6
3.25	2.4
3.55	2.5
4.3	2.9
3.66	2.5
4.32	2.7
4.11	2.5
4.29	2.4
2.99	2.0

As a consequence, the needs occur to be in the range of an on-board actuation device. Of course, the energy consumption due to thermal exchanges must be taken into account to define a wing scale actuator. But the considered results demonstrate that the energy required by the actuation itself is reasonable.

Experimental study of a high strain / stress linear actuator

Actuator's design

A prototype was realised at the laboratory to evaluate the feasibility of a high strain/stress actuator using SMA wires placed parallel to each other and submitted to elastic loads. The experimental device's structure is presented in figure 7.

The aim of this experimental device is the application of intense forces with significant displacements along the SMA wires direction. The realised device is made of 4 Joule-heated

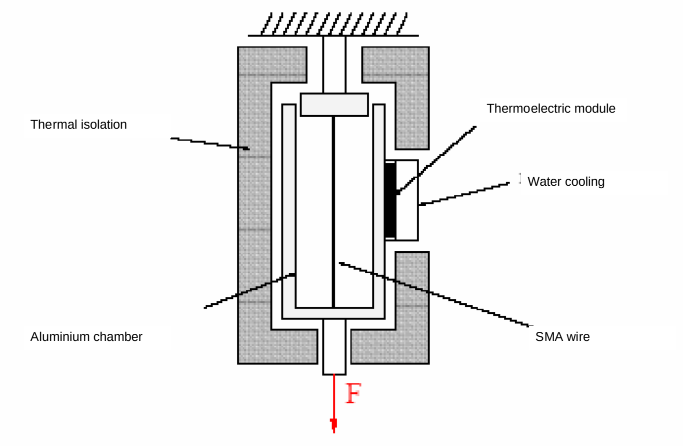

Fig. 7

wires pulling against either a constant or an elastic load.

Experimental results and simulation

A classical approach for modelling shape memory effect is based on a decomposition of the relative strain:

$$S = S_{el} + S_{inel}$$

$$S_{el} = \frac{T}{E(z)}$$

$$S_{inel} = zS_{inel}^{\max}(T)$$

where T is the mechanical stress, S_{el} the elastic stress and S_{inel} the inelastic strain (specific to SMA). $S_{inel}^{\max}(T)$ is the remaining strain of the fully martensitic sample when submitted to T.

To precisely estimate the SMA behaviour, an estimation of the martensite fraction z is required. This may be based on a commonly used phenomenological model like the Liang and Rogers model:

$$z^{A\to M} = \frac{1}{2}\cos\left[a_M\left(\Theta - M_s^0 - \frac{T}{C_M}\right)\right] + \frac{1}{2}$$

$$z^{M\to A} = \frac{1}{2}\cos\left[a_A\left(\Theta - A_s^0 - \frac{T}{C_A}\right)\right]$$

$$a_M = \frac{\pi}{M_s^0 - M_f^0}$$

$$a_A = \frac{\pi}{A_f^0 - A_s^0}$$

where Θ is the temperature and:

$M \rightarrow A$:

$C_A(\Theta - A_f) < T < C_A(\Theta - A_s)$

$A \rightarrow M$:

$C_M(\Theta - M_s) < T < C_M(\Theta - M_f)$

This phenomenological model takes indeed into account the influence of both temperature and stress induced martensite. The precise estimation of z gives the values of the z-dependent parameters like the Young modulus E or the alloy electric resistivity.

It is therefore possible to simulate the SMA actuator behaviour by coupling electrical, thermal and mechanical modelling of the realised device, as shown fig. 8.

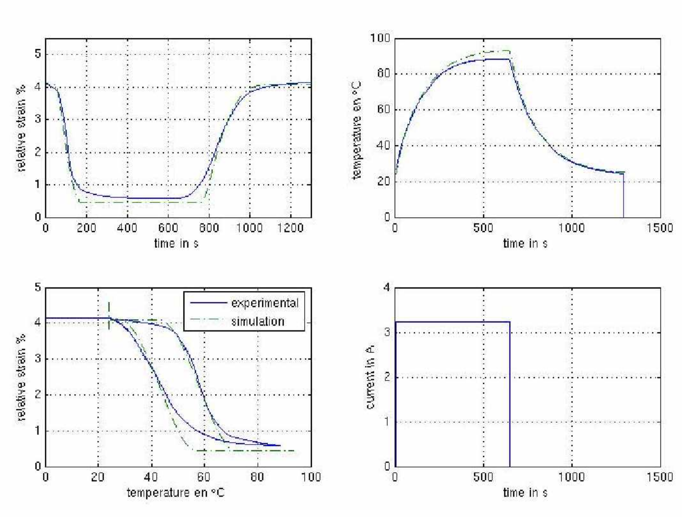

Fig. 8

The experimental device is actuated by four 10cm-long wires. According to these results, the designed actuator is able to apply forces up to 400 N, with displacements in the range of 4 mm.

Design and experimentation of a small scale structure

Description of the studied structure

So as to demonstrate the relevance of the considered actuation mode, an experimental device was realised (cf. fig.9). The aim is to establish the ability of SMA wires to significant deformations of a rigid structure.

This device mimics a small scale wing box structure. The scale is 1/10 when compared to the reference box shown in fig. 4, and the flexional rigidity is in the same range as the corresponding box structure[1].

The actuation is ensured by two SMA

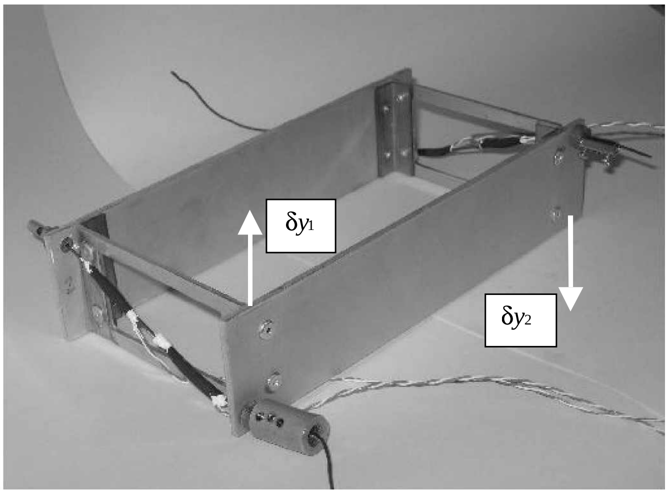

Fig. 9

wires (length: 9cm, diameter: 1mm).

Results and analysis

According to calculus and FEM simulations, the application of a 100N force (which is assumed to be equivalent to the admissible force applied by these wires) along the wire di-

[1] For commodity reasons, the realized device is not the expected thin shell structure, since the thickness would be too low.

rection should produce a significant vertical displacement:

$$\delta y_1+\delta y_1=0.55mm$$

The observed actuator response is reported in fig.10. The displacement amplitude

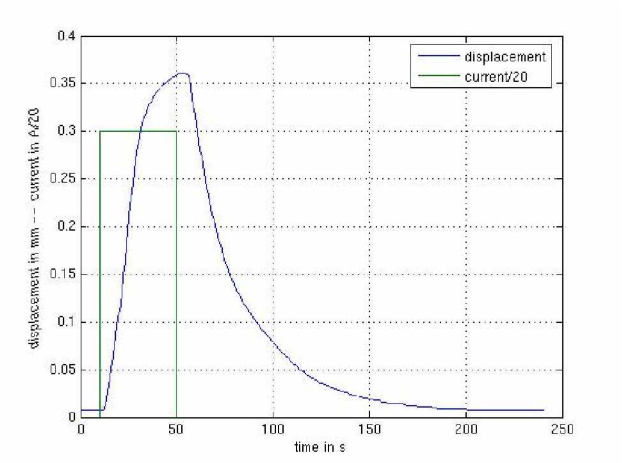

Fig. 10

is close to the expected value (error of nearly 20%).

As a consequence, this experimental device confirms the validity of a SMA global structural actuation. With a 1g nitinol mass, a 0.04° twisting is produced on this small-scale structure. Therefore, SMA wire actuation is likely to produce significant global actuation of large scale realistic wing structures.

Conclusion

This paper focused on the promising potential of shape memory alloys for global airfoil shape control.

After having precised the pros and cons of SMA compared to other electroactive materials, the study reveals the reason why this technology is well suited for quasi-static global shape control when considering their electromechanical performances from a functional point of view. Then, both a structural study and a shape memory effect modelling demonstrated the interest of a distributed actuator structure with a reasonable mass. Finally, an experimental device made it possible to significantly twist a realistic box structure.

Therefore, the way seems to be open for the design of a more achieved actuator structure, aiming at twisting a wing structure at a large scale.

Acknowledgement

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