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A Conceptual Development of a Shape Memory Alloy Actuated Variable Camber Morphing Wing

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Abstract: This study describes the development of a morphing wing concept for a Portuguese Air Force Unmanned Air Vehicle (UAV), the UAS-30. Nowadays, optimized fuel efficiency is a primary requirement in the aerospace industry, and it can be significantly improved by designing adaptive wings which can change their shape in flight to achieve better performance. The UAV research field had concentrated a great industrial effort in the past years by focusing on more intelligent flight technologies but neglecting new approaches using smart materials for developing new wing concepts. Doing the blending between composite structures and smart materials is the perfect way to combine structural robustness and breathtaking mechanical properties while increasing flight performance outputs. By developing a new smart structure, based on a Two Way Shape Memory Alloy honeycomb core with a flexible outer surface, this study proves that it is possible to develop a lighter, more efficient and higher payload capability UAV.

Keywords: Unmanned Air Vehicle, morphing, smart materials, Shape Memory Alloy, honeycomb.

Introduction¹

The UAS-30 is a Portuguese Air Force Unmanned Air Vehicle (UAV) [1] developed to have a Maximum Takeoff Weight of 25 kg, a payload weight of 10 kg, be able to takeoff from a catapult and perform net landing. Its main purpose is to operate as a surveillance device, protecting the coastline, search for wildfires and evaluating the structural conditions of the national pipelines and high voltage pylons and network. In order to do so, an operating speed of 50 km·h⁻¹ is required (a relatively low speed for a fixed wing UAV), leading to its large wing span of 4.5 m and small propeller-driven engine with 5 hp.

With so strict flight requirements, it is mandatory for this aircraft to have a well-designed performance, since every small improvement may lead to better fuel efficiency and longer range. Therefore, optimizing the airfoil for every flight stage by using a lightweight structure may help to meet this goal.

Morphing wings are systems which can adapt themselves during the flight to the most advantageous configuration. Thus, fuel consumption is reduced and the airplane gets more efficient. Nowadays, conventional wings are made using different airfoils along the wingspan, kinking and so forth. In this way, wings may well be optimized for all flight stages in terms of average efficiency, but with the absence of morphing mechanisms there is always a wing portion which is less efficient than it could be for a given flight period. Developing a composite material strong enough to support the aerodynamic loads and flexible in a way that can change its layout during the flight is essential to develop a feasible morphing wing.

To develop such a morphing device, it is necessary to find a solution made of a composite material capable to meet the flight requirements. Giving morphing capabilities to this composite structure demands the use of smart materials, such as Shape Memory Alloys (SMA), in order to develop a feasible smart structure.

Problem Statement

In order to achieve the best aerodynamic performance, an airfoil optimization must be done. Theoretically, this morphing structure is
wanted to adapt to the best configuration for each instantaneous flight condition. However, this is a major effort which would imply dynamic control, fast smart actuators and materials, and a complex structural study. Therefore, and in order to reduce the complexity of the problem while still improving the aircraft performance, the structure will only switch between two configurations: cruise and takeoff/landing. In this way, the optimization will only be performed for this two flight stages, focusing only on the camber morphing of the airfoil. This is done because changing the camber has bigger impact on the aerodynamic properties than changing the chord.

Afterwards, with the geometric data for the two optimized airfoils gathered, the maximum displacement required to switch between both configurations is calculated.

As far as the structure is concerned, a smart material cellular core with a stretchable outer layer honeycomb composite will be used, based on the structure referred by Olympio [2], since it is a structure that can perfectly handle the aerodynamic loads. Given that the outer surface must be flexible, the possibility of applying an auxetic material was investigated since a standard negative Poisson coefficient should not be used in order to avoid material failure. Nevertheless, to simplify the further structural analysis, a zero Poisson coefficient material was chosen meaning that the latter, when stretched in one direction, will not suffer any strain change in other directions.

A simplified sketch, based on the airfoil Althaus AH 79-100 A used in the UAS-30, with a schematic explanation of the bidimensional morphing structure can be seen in Fig.1. There is shown the flexible layer of the honeycomb structure (1), the smart material core (2), and the smart material single wing spar used for this UAV wing (3).

Airfoil Optimization

As stated before, in order to achieve better fuel efficiency it is necessary to adapt the airfoil to the current flight stage. Firstly, it is necessary to estimate the values for the angle of attack (α) and velocity (v) for the flight stages used in the optimization. These rough estimations are based on the data presented in the Portuguese Air Force documents [1] and can be evaluated in Table 1.

Taking these values into account, it is necessary to compute the Reynolds number (Re) at which the airfoil must be optimized. To do so, and since it is a surveillance UAV with low service ceiling, an International Standard Atmosphere (ISA) at Mean Sea Level (MSL) will be considered. The Re is also computed at the airfoil chord (c). Given an approximately rectangular wing with 4.5 m of span (b) and 2.4 m² of surface area (S₀), it leads to c = 0.53 m. The values for Re are shown in Table 1.

<table>
<thead>
<tr>
<th>Flight stage</th>
<th>α/°</th>
<th>v/ (km·h⁻¹)</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff/Landing</td>
<td>12</td>
<td>43.5</td>
<td>4.39×10⁵</td>
</tr>
<tr>
<td>Cruise</td>
<td>0</td>
<td>72</td>
<td>7.26×10⁵</td>
</tr>
</tbody>
</table>

It is now possible to perform the desired optimization. A Computational Fluid Dynamics (CFD) optimization would be much more preferable and may lead to better results in terms of lift to drag ratio improvements. However, it would significantly increase the complexity of the task and be very time consuming. Since the main purpose of this project is to develop a new smart structure, the main design effort may be put on that idea. In this way, a more rough approach based on plot analysis is adopted for this step.

The original airfoil is the Althaus AH 79-100 A, and it was chosen due to its great performance parameters for all flight stages and relative composite manufacturing simplicity. Therefore, an airfoil from this family must be one of the chosen airfoils. Due to its considerably large chamber and high lift to drag ratio (C_L/C_D) at high angles of attack when compared with other options, the AH 79-
100 A can perfectly be the Takeoff/Landing stage airfoil.

With respect to the Cruise stage, a thinner and slightly less cambered airfoil was needed in order to reduce profile drag. The goal was to choose an airfoil specially developed for low speed flight and with the maximum \( \frac{C_L}{C_D} \) close to \( \alpha = 0^\circ \). In Fig.2, plots that supports this decision can be evaluated. The cruise stage airfoil Eppler E64 has the same \( C_L \) value for \( \alpha = 0^\circ \) but smaller \( C_D \) when compared with the takeoff/landing stage one. Therefore, it has a bigger \( \frac{C_L}{C_D} \) and is more aerodynamically efficient for this flight conditions. On the other hand, for the takeoff/landing airfoil, the \( \frac{C_L}{\alpha} \) plot shows the higher stall angle of attack for the AH 79-100 A. \( \frac{C_D}{\alpha} \) plot also shows the lower \( C_D \) value for \( \alpha > 4^\circ \), which also leads to a better \( \frac{C_L}{C_D} \) for this flight stage. This comparison was made with an online airfoil data base tool [3] based on a Xfoil source code for \( Re = 5 \times 10^5 \) and \( N_{crit} = 9 \).

![Figure 2 – Takeoff/Landing and Cruise stage airfoil comparison plots](image)

It can be seen in Tables 2a and 2b the main features for optimized airfoils.

<table>
<thead>
<tr>
<th>Flight stage</th>
<th>Airfoil</th>
<th>Max ( \frac{C_L}{C_D} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff/Landing</td>
<td>AH 79-100 A</td>
<td>116.2 at ( \alpha = 4^\circ )</td>
</tr>
<tr>
<td>Cruise</td>
<td>E64</td>
<td>120.6 at ( \alpha = 3^\circ )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max Thickness /%</th>
<th>Max Camber /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 at 0.279 c</td>
<td>3.6 at 0.565 c</td>
</tr>
<tr>
<td>8.4 at 0.278 c</td>
<td>2.9 at 0.565 c</td>
</tr>
</tbody>
</table>

With the airfoil optimization performed, it is now possible to calculate the maximum displacement \( (d_{max}) \) between both configurations. By storing both airfoil's coordinates [3] and calculating the maximum vertical displacement to change between configurations, it yields to the maximum value of \( d_{max} = 8 \text{ mm at } 0.278 \text{ c} \).

The two final airfoil configurations corresponding to each flight stage are shown in Fig.3.

![Figure 3 – Final airfoil configurations for each flight stage](image)

**Structure Development**

After performing an analysis to the most used smart materials in aerospace, the SMA was chosen as the most suitable solution for this case. A SMA is a metallic alloy capable to change its shape, stiffness and other mechanical properties in response to temperature variations. This means that this smart material is able to return to its original shape, after being deformed, as a response to stated inputs.

The principle behind this feature is the fact that bending an alloy will deform its internal crystalline structure: from twinned to untwinned martensite, and then to austenite. As can be seen in Fig.4, a SMA can stay in a particular crystalline stage between two determined temperatures. When the limiting temperature is reached, the crystalline transformation begins. However, some mechanical energy is lost during the process due to stress level differences between heating and cooling transitions, in a phenomenon called hysteresis.

One other important SMA feature is the superelasticity phase. If the austenitic phase is loaded at a constant temperature \( T > A_f \), phase transformation occurs due to mechanical stress and the alloy is able to recovery from unusually large strain, up to 8 %.

The most simple alloy type is the One Way SMA, which can be deformed and return to the austenitic configuration after being heated. Yet, if some specific treatments were applied to this alloys, they can switch between two predetermined configurations only by heating or cooling, needless to apply any deformation: the Two Way SMA.
Among the wide range of possible applications of this phenomenon, it can perfectly be applied to this smart structure. If the lower temperature configuration corresponds to cruise stage and the higher temperature corresponds to takeoff/landing, this solution can be used. This means that, during the takeoff and landing stage where the aerodynamic loads are bigger and the temperature is higher than in cruise, the SMA can go through its superelasticity phase allowing the morphing airfoil to have huge stra**ins and thus switch between both configurations. In this case, since the UAS-30 operates at relatively low altitudes, this temperature difference between flight stages would not be very significant. But for commercial airplanes, which fly much higher and where temperature difference are actually felt, this can really help in the improvement of the actuation time by accelerating the heat transfer for the SMA.

Therefore, the ability to deal with huge deformations while switching between two predetermined configurations is the biggest advantage of this solution. And this can be achieved using relatively small sized alloys. Given that a SMA can recover from up to 8% strains, to achieve $d_{\text{max}}$ of 8 mm it will be needed an alloy height of 100 mm. Given the chord and maximum thickness (53 mm for the AH 79-100) values, it is only achievable a maximum displacement of 4.2 mm. Therefore, this solution could not be used without further modifications.

As such, the maximum thickness must now be twice the initial absolute value, while thickness to chord ratio have to remain constant in order to keep the aerodynamic properties. Therefore, the chord value must be doubled, leading to a new value of $c^* = 2c = 1.06$ m. In terms of the aerodynamic properties, and since the $C_I/C_D$ is the same, everything remains unchanged if the aerodynamic center and the center of gravity of the UAV stay in the same place. In terms of weight penalty, that will be further analyzed when the final structure weight is estimated.

Taking into account the available materials, the criteria used is based in the phase temperatures [4] and in the average features for off-the-shelf Nickel-Titanium alloys ($\text{NiTi}$) [5,6]. In Table 3, some data can be found for this conceptual alloy with 50.5% of Nickel.

<table>
<thead>
<tr>
<th>$M_s/\degree{C}$</th>
<th>$M_f/\degree{C}$</th>
<th>$A_s/\degree{C}$</th>
<th>$A_t/\degree{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-31</td>
<td>8</td>
<td>44</td>
</tr>
</tbody>
</table>

It can be noticed that the phase temperatures are within the desired range for cruise and takeoff/landing requirements, according to the design previously proposed. Average mechanical properties for the $\text{NiTi}$ SMA are enumerated below:

- Density ($\rho$): 6500 kg·m$^{-3}$
- Elastic Modulus ($E$) for Martensite and Austenite phases: 41 GPa, 83 GPa
- Poisson ratio ($\nu$): 0.33
- Yield Strength ($\sigma_y$) for Martensite and Austenite phases: 140 MPa, 1070 MPa
- Shape Memory Strain ($\varepsilon$): 8%

In order to have a SMA capable of switching between two configurations, it has to pass through a series of treatment processes, called training. This procedure allows the alloy to remember the low temperature shape by applying some mechanical processes based on mechanical deformations. The possible training procedures for a $\text{NiTi}$ alloy are deeply explained by Zanaboni [7].

Regarding the structure, it will be a cellular honeycomb core with flexible skin as the one investigated by Olympio [2], but with different materials. Moreover, the referenced structure aimed to deal with span morphing lateral displacements, whereas the smart structure now developed has to deal with vertical ones. The lateral displacements for this fixed span wing will be further neglected.
**Outer Layer.** The outer layer has been a flexible material. Taking that into account, the possibility of applying an auxetic material was investigated. Standard materials have negative Poisson ratio, which is a drawback for this structure due to the material thickness reduction when loaded in a particular direction. To simplify the further load analysis, a zero Poisson coefficient material was chosen meaning that, when stretched in one direction, the material will not suffer any change in the perpendicular direction to the load. Considering the honeycomb NiTi alloy core, which has similar Elastic Modulus to the investigated Aluminum by Olympio [2], the face-sheet’s material $E$ can be in the order of 0.1 MPa. This matches to many silicone-rubber membranes values, allowing the outer surface to be flexible enough for morphing and smooth for better aerodynamic performance by reducing skin’s friction.

**Honeycomb Core.** Concerning the core, it will be made of vertically-placed hexagonal cellular pattern plates which will fill the whole wing span. In terms of fuel storage this is not a considerable issue, since the UAS-30 does not use the wings as a fuel tank. Actually, they are hollow inside, allowing the wing spar and harness to move freely. Given that the wing spar is chordwise located approximately where $d_{\max}$ is, it means that this structural device cannot be made of carbon fiber as in the original version. This NiTi alloy has good mechanical properties and may well be able to deal with the applied bending moments to the structure. Therefore, all the core is made of the same NiTi SMA. The wing spar is a horizontal massive beam which crosses all the honeycomb structure placed vertically to better deal with the aerodynamic loads. The bidimensional sketch of the honeycomb concept may again be seen in Fig.1.

In order to dimension the smart structure, it is now necessary to physically define the hexagonal cellular-shaped pattern. Given that the maximum thickness for the Althaus AH 79-100 A airfoil is 106 mm, the maximum displacement it can achieve is around 8.4 mm, meeting the criteria of $d_{\max} = 8$ mm for a shape memory strain of 8%.

To calculate the honeycomb core wall’s width, it is firstly necessary to compute the average pressure load for cruise conditions. It is given by:

$$p_t = p_a + \frac{1}{2} \rho v_{cruise}^2 = 1.02 \times 10^5 \text{ Pa} \quad (1)$$

Where $p_a$ and $\rho$ are the static pressure and density at cruise altitude. Since this UAV does not fly at considerably high altitudes, ISA MSL conditions will be assumed. For the velocity $v_{cruise}$ shown in Table 1, it leads to the presented value for $p_t$. This value represents the total wing loading for steady state conditions. Thus, and considering constant lift at cruise and a safety factor (SF) of 1.25, this pressure load can be related with the SMA properties in order to get the NiTi alloy cross sectional area needed to deal with it:

$$\sum F: p_t S_w^* SF = \sigma_y S_{SMA} \quad (2)$$

For the $\sigma_y$ for Martensite and $S_{w}^* = 2S_w$ due to the doubled chord, it is possible to conclude that the cross sectional area for the SMA is $S_{SMA} = 4.3 \times 10^3 \text{ m}^2$. However, it is important to notice that, despite having considered a safety factor, this is a minimum value for the cross sectional area of the SMA. Dimensioning the honeycomb structure in this way would force it to be in the boundary of the elastic regime, which could easily be overcome with a vertical gust. As such, in case of increasing this area, there is a larger safety margin in terms of structural stress.

Considering that every hexagon is completely regular ($\theta = 60^\circ$), each wing has an average of 4 cellular structures chordwise ($d = 265$ mm) and therefore 9 spanwise ($a = 306$ mm), which will lead to an average of 36 hexagons each wing. Taking into account the hexagon’s 6 walls ($l = 153$ mm) and the whole honeycomb structure, the minimum allowed wall thickness ($t$) is 0.13 mm. The geometric data can be found in Fig.5.

As a result, and in order to fulfill the safety margins, it is advisable to increase the wall thickness so that one can mitigate the risk of plastic deformation. Therefore, the wall thickness is increased to 0.8 mm, leading to a final honeycomb structural weight of 2.8 kg.
In Fig.6, one can see the CAD final render of the hexagonal honeycomb core. There also can be found a spar hole which allows the connection with the UAV fuselage.

**Implementation**

With respect to the structure implementation, it will lead to a new concept of wing design. Since the wing is completely made of this smart structure, there is no need for ribs. The honeycomb composite structure is more resistant to the pressure loading, and all the bending moments are supported by one spar, also deformable and made of SMA. It is important to refer that, despite being made of the same material and being vertically oriented, this two components must have a tolerance between each other and must not be stuck. This is not only to allow some structural wing displacement with respect to the wing spar, but also to permit the heating of the spar. Actually, the positioning of both heating and cooling systems is one of the most important features of this structure and will be further discussed.

**Heating System.** The positioning and operating method of the heating system is crucial for its good performance. Heating is going to take place during the takeoff and in the beginning of the approach when the airfoil needs to go through its superelasticity phase. While on the ground, heating above $A_f$ is not a critical issue since the temperature difference is small. During cruise, the UAV is at its maximum speed and altitude, and heat losses due to forced heat convection are going to happen. Their impact on the overall heat transfer process will only increase with the increasing of the temperature difference between the honeycomb core and air. The core temperature will increase due to the action of the heating system, but the temperature difference will not increase that much because the airplane is slowing down and descending, decreasing the importance of forced convection phenomenon.

In order to heat up the SMA core, electrical resistances will be triggered by the increasing pressure values read by the altimeter and start consuming some engine power to initiate the airfoil transformation. This resistances will dissipate heat to the vicinity, due to Joule effect, and increase the alloy's temperature by conduction. The resistances will be integrated in the airfoil flexible skin and its *modus operandi* is similar to car's window defoggers. Thin electric wires are installed in the outer layer of the composite and will dissipate heat to the core. In order to ensure that the inner parts of the core and specially the spar are heated properly, this wires should also be installed in the tolerance gap between the spar and the core. In this way, it is possible to ensure a more constant heat flow throughout the structure and ensure that all the SMA is equally heated.

To roughly estimate the power needed to heat the SMA, the Lumped Capacitance Method is applied based on the Heat Transfer theory for Transient conditions. Its main assumption relies on the uniform temperature distribution throughout the transient process, meaning that $T(\vec{r},t) \approx T(t)$. Firstly, a general case which includes convection, radiation, an applied heat flux to a specific surface and internal energy generation is considered. The general equation is given by an energy balance.

$$\dot{E}_{st} = \frac{dE_{st}}{dt} = \rho V C \frac{dT}{dt} = \dot{E}_{in} + \dot{E}_{gen} - \dot{E}_{out}$$

(3)
If Eq.3 is transformed into the following differential equation, considering that \( \theta(t) = T(t) - T_{∞} \), it follows that:

\[
\frac{dθ(t)}{dt} + a \theta(t) - b = 0
\]  

(4)

For Eq.4, one of the well-known exact solutions may be applied to the SMA concept, which consists in neglecting radiation, internal energy source and sink terms. As such, the solution is presented as follows:

\[
\frac{T(t)-T_{∞}-b/a}{T_i-T_{∞}-b/a} = e^{-at}, \quad a = \frac{\hbar A_{\text{conv}}}{\rho V C}, \quad b = \frac{\dot{q}}{\rho V C}
\]  

(5)

In which \( h \) is the heat convection coefficient, \( V \) the volume and \( C \) the specific heat of the SMA.

However, for this theory to be applicable, it must meet the condition of the *Biot number* (*Bi*) much smaller than 1. Considering the characteristic length of the heat transfer (\( L_c \)) as the maximum airfoil thickness (106 mm), usual values for forced convection on air (\( h = 25 \text{ -}250 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \)) and an average value for the thermal conductivity of the SMA NiTi alloy (\( k = 56.3 \text{ W} \cdot \text{m}^{-1} \cdot \text{K} \)), it follows that \( Bi \approx 0.04 << 1 \). Therefore, this method is applicable.

In this situation, the power needed to change between configurations in 60 seconds is unknown. Thus, the purpose is to estimate the heat the resistances need to dissipate to force the SMA to go through its Austenite phase, from 8 °C to 44 °C. The time gap \( t = 60 \) s is considered to be a feasible interval for a runway approach. Solving Eq.5 in order to \( \dot{q} \) and considering the heat equally distributed by the hexagonal walls in every wing, it follows that \( \dot{q} = 870 \text{ W} \).

To conclude, it is possible to state that the engine has to provide at least 870 W for 1 minute to each wing to change its shape. Considering the 5 hp motor which drives the UAV, this is a considerably acceptable value.

**Cooling System.** The cooling phase will occur during the takeoff and climbing, and takes advantage of the increasing heat transfer coefficient and temperature difference. In the same way the heat convection impact decreases during the approach phase, it increases during the climbing due to the inverse phenomenon. In order to cool the SMA core, the heat transfer will occur either by conduction and convection. The skin material must be porous enough to provide a proper but small airflow to the cellular structure in order to increase the heat transfer. To ensure that the inner parts of the core and the main spar are able to lower their temperature, a new solution must be applied in this structure. As can be seen in Fig.7, a set of holes will be installed throughout the wing span, equally spaced, in order to provide a small air flow to the inner parts of the structure. This holes will make a sort of a pipe through the wing structure and are located on the lower skin, below the leading edge. This happens because this feature must be optimized for the climbing stage, where \( \alpha = 12 \, ^\circ \), and thus it should be lined up with the stream direction. For the same reason, this pipe must be diagonally oriented instead of horizontally, allowing the maximization of the velocity in the pipe and therefore the convective heat transfer. It is still important to highlight that these holes have to be small, with a diameter in the order of millimeters, in order not to trigger transition to turbulent regime in the airfoil.

![Figure 7 – Cooling system layout](image)

As previously done for the heating system, an estimation will be conducted in order to assess the time necessary to cool the whole wing. The same Lumped Capacitance Method is used. However, it is important to state that the honeycomb core will only be cooled through forced heat convection driven by air, and no other cooling methods would be used. Data will be computed for the temperatures suggested in the SMA properties, which for the Martensite phase corresponds from 5 °C to -31 °C. As stated before, the UAV does low altitude missions, and therefore does not achieve such temperature.
Despite that, the calculations will be performed to prove whether or not this cooling method is feasible for larger aircraft which actually does the cruise at such altitude and temperature.

Firstly, it is necessary to calculate the Prandtl number \((Pr)\), the rate between advection and thermal diffusion. Considering normal values for air at 300 °K, one can get that \(v = 15.89 \times 10^6 \text{ m}^2\cdot\text{s}^{-1}\) and \(\alpha = 22.5 \times 10^6 \text{ m}^2\cdot\text{s}^{-1}\.

Computing the Prandtl and Reynolds number \((V_{cruise} = 72 \text{ km}\cdot\text{h}^{-1})\), this leads to the following expression for the Nusselt number \((Nu)\) for an external stream forced convection over a flat plate at turbulent regime:

\[
Pr = \frac{\nu}{\alpha} = 0.71, \quad Re_L = 1.34 \times 10^6 \\
\Rightarrow Nu_L = 0.037Re_L^{4/5}Pr^{1/3} \approx 2630
\]

Given that, and by definition, the Nusselt number is given by \(Nu = hL/k\), and considering the characteristic length as the chord and \(k = 26.3 \times 10^{-3} \text{ W} \cdot \text{m}^{-1} \cdot \text{K}\) for air at 300 °K, one can get that the forced convection coefficient is \(h \approx 65\). As such, it is possible to estimate the heat lost by convection during this process, taking the desired temperature as -31 °C and the temperature from the surroundings as 25 °C.

\[
\dot{q} = hA_{\text{conv}}(T - T_\infty) = -235 \text{ W}
\]

In this way, and given that the conditions for applicability remains the same than the ones stated for the heating problem, the Lumped Capacitance Method is applicable. Solving Eq.5 in order to time, it is possible to get that \(t \approx 1200 \text{ s} = 20 \text{ min}\).

In conclusion, 20 minutes to change between configurations is a considerably long time interval for the UAV mission requirements. This aircraft will perform missions no longer than 1 hour, and therefore this time gap is too large. Yet, for larger aircraft with longer flight time, this solution has some potential to be studied. However, it would be preferable to apply other complementary cooling devices to accelerate the heat transfer.

**Flight Profile.** In order to design a proper flight path and summarize all the flight stages at which the heating and cooling systems are on, a flight profile is presented in Fig.8.

![Flight profile scheme](image)

It is possible to assess that the need for the heater turned on above 44 °C during takeoff and descending is justified by the demand for the SMA go through its superelasticity phase, dealing with 8 % strain. Only in this way is possible to meet the strain goal and morph to a thinner airfoil during cruise.

**Conclusions**

In order to conclude about the worthiness of this smart structure when compared with the original one, it is necessary to perform a weight analysis. The original wing mass, with a carbon fiber structure, is around 4 kg each wing. Taking into account \(d_{\text{max}}\) and \(\rho_{\text{SMA}}\), and as stated before, the honeycomb core weighs 2.8 kg. Considering the silicone-rubber membranes for the outer skin, much less dense than the core, one can roughly estimate that the mass the wing would have is approximately 3 kg. Therefore, each wing weighs 25 % less than the original one, meaning the increasing on the payload weight of 20 %. This is remarkable since the wing chord and therefore the wing area were doubled in order to fit the morphing mechanism.

Also, a lighter aircraft enables a better fuel efficiency. Moreover, and since the airfoils are optimized for two flight stages, the aerodynamic performance is better than the original, increasing its overall performance. In general, it is possible to conclude that this smart structure made this UAV lighter and more efficient. This means that this concept airplane has now a larger payload weight, lower fuel consumption and longer range.

Concerning the drawbacks of this smart structure, the structural and functional fatigue will always be a problem due to the large cyclic...
strains this material has to deal with. This fatigue limits need to be carefully studied before adopting this solution. Other feature against this solution is the cost. Despite being easier nowadays to produce this kind of solutions, the manufacturing of a honeycomb composite and specially the training procedures of a Two Way SMA is still too expensive.

As far as future improvements are concerned, further structural and aeroelastic analysis should be performed. Since it has a long wing span, the aeroelastic phenomena and consequent bending moments in the spar have increased importance in the structural behavior of the aircraft. A better airfoil optimization, using an iterative CFD process, would also be positive despite the need to keep the maximum displacements low in order to fit the structure inside the wing.

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