NUMERICAL ANALYSIS OF A DRONE BIO-INSPIRED MORPHING WING ACTUATED BY SHAPE MEMORY ALLOY ELEMENTS

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Abstract. Smart materials are able to change their characteristics and properties when subjected to different external fields, such as thermal, mechanical or magnetic. Shape memory alloys (SMAs) are one of the main smart materials used today. Due to their remarkable capacity to develop large forces and displacements, SMAs are suitable for actuators employed in the aeronautical industry, among others. An important application of SMA actuators occurs in the field of morphing wings for aircrafts. Through this approach, different geometric wing configurations can be used to meet different conditions during flight. In order to analyze the state of the art regarding this technology, a search was conducted in patent databases seeking morphing wings actuated by SMAs elements. 65 patent documents filed between 1991 and 2019 were found, where about 43% were filed since 2015. In this paper, a proposal for a drone bio-inspired morphing wing structure actuated by SMAs is presented. A constitutive model with internal variables is used to represent the SMA behavior. Numerical simulations were carried out using a finite element model to study the performance of the morphing wing for different flight conditions. These simulations show that the proposed structure when actuated by the SMA element under a proper thermomechanical loading achieves an increase of approximately 5 % in maximum lift that is useful for take-off phase of flight and an increase of approximately 31% in lift at zero angle of attack that is advantageous for maneuvering control. The proposed methodology can also be used to assess the performance of morphing wings for different flight conditions in order to establish optimal geometric configurations.

Keywords: smart structures, shape memory alloys, morphing wings, bioinspired design

1. INTRODUCTION

Modern technological development has allowed the design of intelligent devices and structures capable of operating in different environments and adapting to external stimuli. A fundamental approach to developing such smart devices is to take inspiration from existing systems in nature. Biological structures and their underlying mechanisms and principles have the potential to generate new ideas and to improve design of conventional robotic devices and controls (Egan *et al.*, 2015). The bio-inspired devices are projected based on observations of how living beings walk, swim, crawl, jump or even fly. Nature-inspired devices and structures are becoming increasingly important in engineering in the face of complex applications. By bioinspiration, structures that are innovative, flexible and adaptable to different environments have been emerging, especially in robotics applications (Fukuda *et al.*, 2018). Bioinspired technologies have emerged mainly in the areas of intelligent materials and structures, sensors and actuators, modeling and control of manipulators similar to biological members, and the shape control of flexible systems. Some examples of applications of these technological developments are deformable airfoils, modeling and control of anthropomorphic manipulators, and muscle activation and control modeling for human limb prosthesis and orthotics applications (Lakhtakia and Martín-Palma, 2013). Intelligent materials and systems are of great interest in bioinspired designs since they can adapt to changes in

environmental and operating conditions through changes in their physical properties. Smart materials include piezoelectric polymers and ceramics, magneto-rheological fluids, magnetostrictive materials, and shape memory alloys (Soh *et al.*, 2012). Shape Memory Alloys (SMAs) have remarkable features and behaviors, which are associated with microstructural transformations. These metal alloys are so named because they exhibit the ability to recover their initial shape after an appropriate thermomechanical cycle. Furthermore, under certain conditions, SMAs absorb and dissipate mechanical energy through a hysteretic and reversible shape change when subjected to cyclic mechanical loading. Such distinctive features of SMAs are responsible for the popularity of these alloys for applications related to sensors and actuators (Lexcellent, 2013; Lagoudas, 2008). Some applications of SMAs in the aerospace industry include hydraulic couplers, wing twist control mechanisms, variable geometry chevrons and adaptive trailing edge flaps. However, one of the main limitations for the use of SMAs is their susceptibility to fatigue failure. In addition to the cyclic load variation, a typical cause of fatigue in conventional materials, SMAs have other forms of fatigue. As these alloys undergo phase transformations, the physical motion of the atoms associated with this phase transformation is commonly an additional source of fatigue. Thus, fatigue in SMAs can be decomposed into structural fatigue, which is due to high cyclic loads, and functional fatigue, due to successive phase transformations that lead to a deterioration in the functional properties (Phillips *et al.*, 2019; Dornelas *et al.*, 2021).

This paper aims to disclose a design of an adaptive aircraft wing with variable geometry airfoil sections actuated by SMA elements. A discussion of SMAs comprising general aspects of such alloys, such as history, topics on metallurgy, thermomechanical behavior of such alloys and mathematical modeling thereof is also presented. Furthermore, concepts regarding adaptive aircraft are introduced, as well as examples of changes in geometry and configuration of aircraft elements, such as wing, fuselage, propulsion system and empennage. A brief discussion of the state of the art regarding morphing wings actuated by SMA elements is presented, including a search in free databases for patent documents related to such devices, in order to map the available technological information about those morphing wings. Lastly, results of numerical simulations using the panel method and the finite element method are shown so as to analyze the aerodynamical and mechanical behavior of the proposed structure.

2. ADAPTIVE AIRCRAFTS AND MORPHING WINGS

Adaptive aircraft can be defined as one that modifies its shape to maximize its performance under radically different flight conditions. Adaptive aircraft design commonly aims to maximize efficiency at all stages of flight and/or allow for different missions that would otherwise require different aircrafts to be performed. Adaptive aircraft adapt to multi-objective mission profiles, operating with greater efficiency (Tavares *et al.*, 2017). Such configuration changes can occur in any part of the aircraft, such as the fuselage, wing, propulsion system and empennage. Changes in wing shape are the most important aspect of adaptive aircraft as this element dictates the performance of an aircraft in a given flight condition. These changes in wing shape have interested aircraft designers since the early days of aviation, progressing from control surface design even wings with variable bending. For instance, the Wright Flyer and Alberto Santos-Dumont's Demoiselle allowed rotation control by altering the twist of their wing using cables directly actuated by the pilot (McMasters, 2004; Moens, 2019). The growing demand for higher cruise speeds, payloads and efficiency has promoted the development of several solutions. The ability of a wing surface to change its geometry during flight has interested researchers and designers over the years. Conventional flaps or slats have been used on aircrafts to change the geometry of its wings during specific stages of the flight. Morphing wing can be a complementary solution by using a wing that is inherently deformable and adaptable (Stanewsky, 2001). The ability of a wing surface to change its geometry during flight has interested researchers and designers over the years, as a morphing wing allow the aircraft to operate in multiple flight conditions. In this sense, nature offers several examples of animals capable of flying agilely and controlling this flight efficiently (Dimino *et al.*, 2017; Lilienthal, 1889).

Recent discoveries in bird flight mechanics and new bioinspired ideas have led many researchers to reconsider birds as models for adaptive aircraft. In the early 2000s, some research projects were supported mainly by the Defense Advanced Research Projects Agency (DARPA) and the National Aeronautics and Space Administration (NASA) in the States United, focused on more pronounced configuration changes, for example, 200% variation in aspect ratio and 50% in wing area, 5° change in wing twist and 20° change in sweep angle in order to allow for development of truly multi-mission aircraft (Valasek, 2012; Kudva *et al.*, 2002). In many cases, the differences between animal flight requirements and engineered flight systems are substantial, yet there is significant potential for studying nature and applying its lessons to solve challenging problems involving flight (Raney and Waszak, 2003). Specifically in the case of small aircraft, such as unmanned aerial vehicles (UAVs), the flight of animals serves as an excellent basis for inspiration, as often, flight conditions such as speed and Reynolds number, typically faced by birds and UAVs are similar (Ananda and Selig, 2018). Hence, UAVs are ideal platforms for experimenting with new concepts and testing new structural solutions because of lower certification requirements and safety restrictions compared to other aviation sectors. The growing interest in adaptive aircraft is also fueled by the diversity and availability of intelligent materials, such as SMAs and shape memory polymers (SMPs), which enable the design of small, lightweight actuators (Gomez and Garcia, 2011).

The wing is the most influential component of an aircraft, as it creates most of the lift required for flight. Furthermore, the shape and size of the wing determine the suitability of the aircraft for a particular mission. Modifications in wing geometry and configuration are extremely challenging and can be conceptually achieved in a variety of ways: folding,

hiding, telescopically moving, expanding and contracting a wing, attaching and detaching multiple wing segments, etc. (Jha and Kudva, 2004). Barbarino et al. (2011) classify morphing wings into three classes: a) wing planform alteration, which comprises the subclasses of variable span, chord morphing and variable-wing sweep; b) airfoil adjustment, which includes the subclasses of camber morphing and thickness morphing and c) out-of-plane transformation, which comprises the subclasses of twist, dihedral/gull, and span-wise bending. Particularly, the airfoil camber adjustment has been the most morphing method used and it is most achieved through deflections at the leading and trailing edges. There are many reasons for this trend: - the variable camber can result in significant performance benefits, especially in the lift/drag ratio; the rigid structure of the traditional leading and trailing edges can be replaced by morphing wing structures and independent non-uniform transformation of these adaptive structures can result in wing torsion; smoothly modified leading and trailing edges can be used as more effective control surfaces compared to discrete and discontinuous ailerons, flaps, elevators, and fins; and the alteration of leading and trailing edges can be restricted to two-dimensional plane movement, thus simplifying the analysis (Vasista *et al.*, 2012). For these reasons, the variable curvature of the wing profile through the transformation of the leading and trailing edges has been the most viable parameter for the transformation. Hence, changes in wing geometry directly influence the aerodynamic characteristics of the aircraft, such as lift, drag, efficiency and maneuverability. Morphing wings can generate some benefits such as reduced drag and vibration, as well as increased performance and flight envelope (Dimino *et al.*, 2018).

3. SHAPE MEMORY ALLOYS

SMAs are metallic materials that present complex thermomechanical behavior and have unique properties. These characteristics of SMAs occur due to martensitic phase transformations, which, for such alloys, can be induced by temperature and/or mechanical stress. SMAs can basically exist in two phases: a) a high-temperature stable phase having a cubic crystal structure, called austenite, and b) low-temperature stable phase, which can have an orthorhombic, tetragonal or monoclinic crystal structure, called martensite. In SMAs, the martensitic transformation occurs without diffusion of atoms, but rather by distortion of the shear structure. The crystals that form the martensitic phase may orient themselves randomly or may have a preferential orientation direction. Twinned martensite is characterized by the random orientation of the crystals, while detwinned martensite presents an alignment of these crystals (Funakubo, 1987). Currently, NiTi alloys are the SMAs of greatest commercial and industrial interest due to their unique characteristics (Mwangi *et al.*, 2019). Such NiTi SMAs exhibit better properties in near equiatomic compositions (Otsuka and Ren, 2005). The complex thermomechanical behavior of SMAs, which is caused by the microstructural transformations that these alloys may undergo, enables their functional features. Specifically, SMAs have been one of the most used materials in morphing wing designs, particularly as actuators to modify the airfoil curvature or wing twist angle. SMAs stand out in these applications because they can act as an actuator and simultaneously act as a structural element. An important feature of SMAs that suit morphing wing designs is their reduced weight-to-produced power ratio, which allows for the development of actuators capable of performing configuration changes without penalize the aircraft weight. Another great advantage of using SMAs as actuators for morphing wings is that such alloys develop and recover considerable deformations (Barbarino *et al.*, 2011). The main phenomena of interest that SMAs present are the shape memory effect and pseudoelasticity, which are related to the martensitic phase transformation. SMAs exhibit the shape memory effect when they are deformed in the twinned martensitic phase and then unloaded while at a temperature below austenitic start temperature at zero stress. When it is subsequently heated above austenitic finish temperature at zero stress, the SMAs will recover their original shape by transforming back into the parent austenitic phase (Lagoudas, 2008), as illustrated in Figure 1.
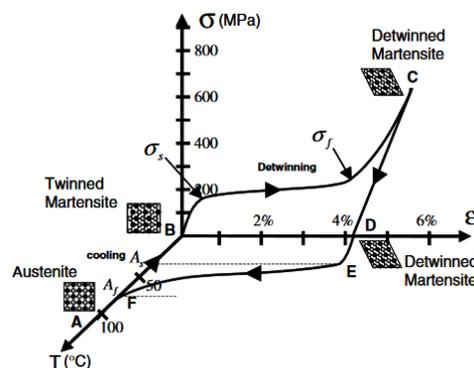

Figure 1. Stress-strain-temperature data exhibiting the shape memory effect for NiTi SMA (Lagoudas, 2008).

The model proposed by Auricchio and Petrini (2004), which explores concepts from the theory of elastoplasticity, was adopted in this paper since it is the constitutive model implemented in the finite element analysis software ANSYS, which will be used in the numerical simulations carried out. This model is developed from the Helmholtz free energy potential theory, as shown in Eq. (1):

$$\psi(\varepsilon, \varepsilon_{tr}, T) = \frac{1}{2}E(\varepsilon - \varepsilon_{tr})^2 + \beta\langle T - M_f\rangle\,\|\varepsilon'_{tr}\| + \frac{1}{2}h\|\varepsilon'_{tr}\|^2 + I_{\varepsilon'_{tr}}(\varepsilon'_{tr}) \tag{1}$$

where E is the elastic stress tensor of the material, ε is the total strain, ε_{tr} is the total transform strain, ε'_{tr} is the deviatoric transform strain, β is a material parameter, T is the temperature, M_f is the temperature below of which austenite is not observed in a stress-free state, h is a material parameter related to material hardening during phase transformation and $I_{\varepsilon'_{tr}}(\varepsilon'_{tr})$ is an input function to satisfy the restriction in the transformation strain norm defined in Eq. (2):

$$I_{\varepsilon'_{tr}}(\varepsilon'_{tr}) = \begin{cases} 0 & 0 \le \|\varepsilon'_{tr}\| \le \bar{\varepsilon}_L \\ +\infty & otherwise \end{cases} \tag{2}$$

Generally, the elastic moduli of austenite and martensite are different in SMAs. Thus, it is noted that during the phase transformation, the elastic stiffness tensor, E, varies with strain. Equation 3 defines the elastic stiffness tensor as a function of the transformation strain, ε_{tr}, where E_A is the elastic stiffness tensor of austenite and E_M is the elastic stiffness tensor of martensite:

$$E = \frac{\|\varepsilon'_{tr}\|}{\bar{\varepsilon}_L}(E_M - E_A) + E_A \tag{3}$$

In this model, the Poisson's ratio of austenite and martensite are considered equal.

4. PATENT SEARCH FOR MORPHING WINGS ACTUATED BY SMA ELEMENTS

The patent search disclosed in the present work was restricted to documents that include in their specification and set of claims, expressions like "morphing wings", "adaptive wings", "reconfigurable wings", "actuator", "shape memory alloy", "nitinol", "memory metal", "memory alloy" among others. In addition, documents were restricted to international patent classification B64C, which refers to airplanes and helicopters.

From this search, 65 patent documents filed between 1991 and 2019 were found. The number of patent document publications regarding this technology has increased considerably in the last decade, with peaks in the years 2012 (9 documents) and 2017 (10 documents). Furthermore, about 43% of the patent documents were filed since 2015. The patent documents found are grouped into 54 patent families. It is worth mentioning that a patent family is a set of patent documents filed in different countries with the purpose of protecting a given invention. Moreover, before being published, patent documents typically remain confidential for 18 months from their filing. Thus, documents still in secrecy were not indexed in the patent database. The main applicants are shown in Figure 2(a). The company with the largest number of patent documents referring to morphing wings actuated by SMA elements was Boeing, with 13 documents, followed by the Chinese institute Shenyang Aircraft Design Institute, with 4 documents. Other relevant institutions in the aeronautics/aerospace industry such as NASA, EMBRAER, Airbus and Raytheon are listed among the main applicants (2 documents each).

Figure 2(b) shows the jurisdictions with the greatest number of documents relevant to this technology. The analysis by jurisdictions with the highest number of patent applications seeks to point out the regions where there is greater interest in protection by economic agents. It appears that the country with the highest number of filings of relevant documents is the United States, with 38 documents (58% of the total), followed by China, with 11 documents, as well as 6 documents filed at the European Patent Office and 3 filed in South Korea. In addition, there are 5 applications filed via PCT (Patent Cooperation Treaty) among the documents considered relevant. This highlights the interest in protecting technologies associated with adaptive wings actuated by SMA elements in major global economies.

In order to investigate in which countries technological information regarding morphing wings actuated by SMA elements is produced, the country of origin of the inventors of patent applications referring to this technology was also analyzed. In this regard, 27 documents have North American inventors, 12 documents are from Chinese inventors, 4 documents are from German inventors and 3 documents are from South Korean inventors. Two documents are from Brazilian inventors and the other two are from Italians. Countries like Canada, Spain, France, Great Britain, India and Japan are also the origin of the inventors of patent documents for this technology (one document for each of these nationalities).

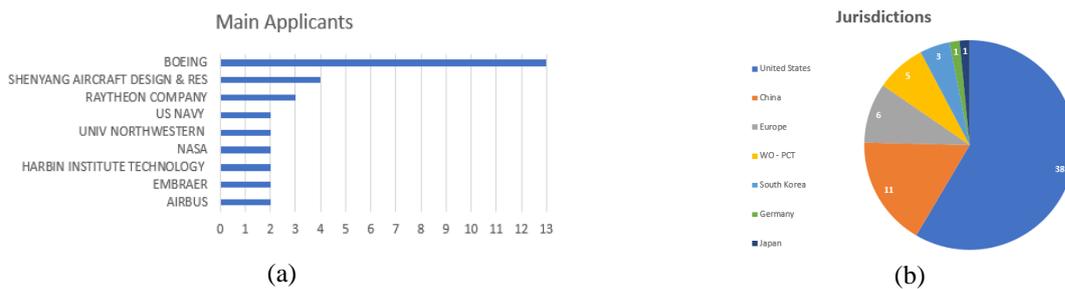(a)   (b)

Figure 2. (a) Main applicants for documents regarding morphing wings actuated by SMA elements (b) Jurisdictions with the highest number of relevant documents –from data obtained in Lens (2021).

Figure 3 shows the five international patent classifications with the highest number of relevant documents. The classification of patents present in a larger number of documents was the adjustment of the wings through the variation of the airfoil camber (B64C3/44). Other notable applications were the adjustment of the wings by varying the airfoil camber through relatively mobile parts of the wing structures (B64C3/48), mechanisms producing mechanical force using the expansion or contraction of bodies due to heating, cooling, drying or similar (F03G7/06), adjustment of the wings by means of area variation (B64C3/54) and adjustment of complete wings or parts of them (B64C3/38).
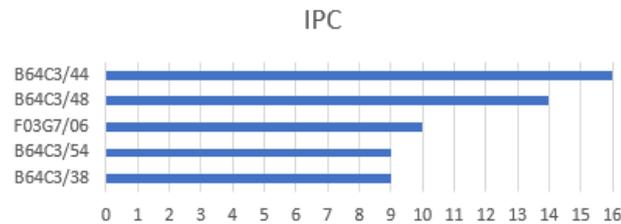
Figure 3. Five international patent classifications with the highest number of relevant documents – from data obtained in Lens (2021).

5. PROPOSED GEOMETRY AND NUMERICAL SIMULATIONS THEREOF

The morphing wing disclosed in the present paper comprises wing sections that are actuated by SMA elements. This morphing wing is designed for small aircrafts, especially for unmanned aerial vehicles (UAVs). Figure 4 illustrates the geometry proposed in this work. The proposed geometry comprises a rectangular wing having a wingspan of 2 m and a chord length of 0.4 m and a flexible skin intended to form a continuous surface during the alteration of shape of the wing. Although the flexible skin is an important feature in the present design, a detailed design thereof will not be included in the scope of the current work and it is assumed that its stiffness is much lower than the stiffness of the airfoil structure and, thus, the influence of this flexible skin can be despised. The selected airfoil is the S1223 (Selig et al., 1995), which profile belongs to the high lift low Reynolds profiles class, suited for unmanned aerial vehicles, and the aircraft is designed to have a total mass of 30 kg. A SMA wire having a diameter of 0.2 mm and a length of 54 mm is positioned on the lower surface of the airfoil of each wing section so that, when this wire is heated, the reduction in length of the SMA wire promotes the actuation of the trailing edge of the wing section. After heating, a mechanical locking system is used for maintaining the geometry. Such actuation is configured to generate an increase in the camber of the airfoil, aiming an increase in the lift force. After cooling the SMA wire by convection, the torsion spring, which is positioned in the airfoil's hinge, biases back the structure of the airfoil.

Therefore, the proposed morphing wing is designed to have two configurations. The first configuration, defined after heating the shape memory element and the consequent deformation of the airfoil trailing edge, has a greater curvature and is suitable for take-off situations. The second configuration, after the cooling of the shape memory element and the restitution promoted by the torsion spring, is suitable for cruise flight. In other words, the purpose of the proposed adaptive wing is to make the aircraft take off with a shorter runway length and that, when cruising, it allows for a reduction in energy consumption, thus increasing the vehicle's flying range. Figure 4 also illustrates a portion of the finite element analysis (FEA) mesh and the boundary conditions used in the simulations.
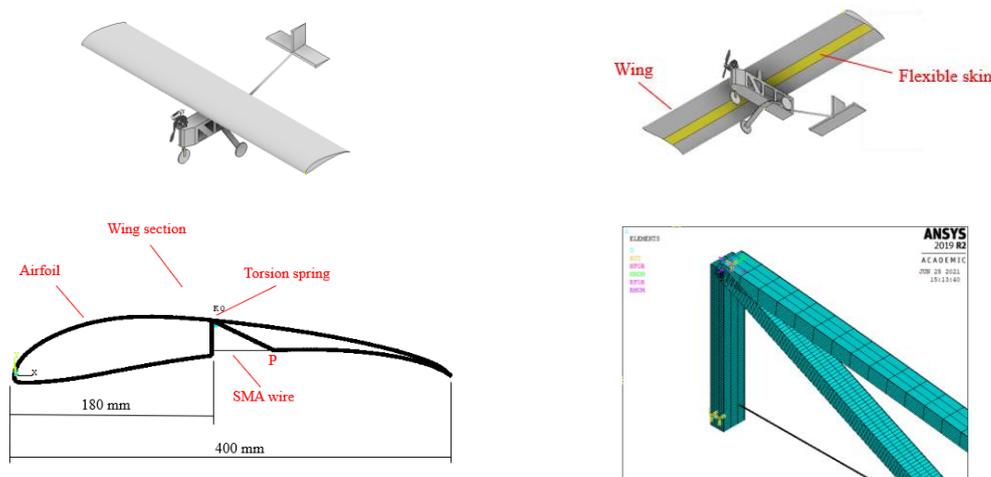

Figure 4. Proposed geometry and FEA mesh.

The proposed geometry was modeled and analyzed using the finite element analysis (FEA) software Ansys 2019 R2. The material selected for the airfoil was the polylactic acid polymer (PLA), often used in 3D printers. The mechanical properties of PLA used in the simulation were the elastic modulus of 3.5 GPa, Poisson's coefficient of 0.36 and yield strength of 50 MPa (Farah, 2016). The airfoil was modeled using BEAM188 beam elements, due to the versatility of this type of element, as well as the various possibilities of cross-section geometries. The cross section of the airfoil is rectangular with a width equal to 5 mm and a height equal to 3 mm.

The torsion spring was modeled as a COMBIN14 element, which is a spring element. The elastic constant of the selected torsion spring is 1000 N.m/rad. The SMA wire was simulated as a BEAM188 beam element. This element was chosen since it not only reproduces the geometric features of the wire, but also because this element supports the TB, SMA function of Ansys, which is the function that reproduces the behavior of SMAs. The parameters of the SMA wire implemented in this simulation are presented in Table 1. The austenite elastic modulus of the SMA wire is 45 GPa and the Poisson's ratio thereof is 0.33. The selected SMA wire also has a specific mass is 6448.1 kg/m^3, an electrical resistance of 2 Ω/m and a specific heat capacity of 6448.1 J/(kg·°C) (Pereira, 2009).

Table 1 – Shape memory wire parameters (adapted from Ford and White, 1996).

Parameter	Value	Description
C1	1 GPa	Hardening parameter
C2	315.15 K	Reference Temperature
C3	50 MPa	Elastic limit
C4	7 MPa/K	Temperature scaling parameter
C5	0,07 mm/mm	Maximum transformation strain
C6	25 GPa	Martensite elastic modulus
C7	0,0	Lode dependency parameter

The system is modeled as a lumped system (Pereira, 2009) and thus, the heat transfer is governed by equation (4):

$$\rho V r - h_{conv} A (T - T_{amb}) = c \rho V \frac{dT}{dt} \tag{4}$$

where ρ is the specific mass, V is the volume of the wire, r is the heat generation per unity of volume provided by an external source of energy, h_{conv} is the heat transfer coefficient, A is the convection surface area, T is the body temperature, T_{amb} is the environment temperature and c is the specific heat capacity. In the numerical simulations, The SMA wire is heated by an electric current of 1 A during 20 s in each heating cycle and the convection coefficient adopted is 20 W/m^2. In order to simulate the airfoil camber variation through the activation of the SMA wire, a thermomechanical loading was simulated. In the initial state, the SMA wire is at environment temperatures of 8, 13, 18, 23 and 28 °C.

The wire is then submitted to a mechanical load (prescribed displacement) until it reaches a strain of 5%. At this point, the free end of the wire is fixedly attached to the trailing edge of the airfoil. After attaching it to the structure, the wire is heated by the electric current for complete austenitization of the SMA, thus deforming the trailing edge of the airfoil. The wire is then cooled by free convection and is biased back by the torsion spring. A subsequent thermal cycle comprising another heating and cooling steps is performed to evince the periodic response of the system.

Figures 5(a)-(e) show the thermomechanical behavior of the SMA wire subjected to the thermomechanical loading proposed. It can be noted that for each environment temperature tested, the strain, stress and detwinned martensite fraction after the heating loads (time = 120 s and 240 s) were the same, as well as at the end of the cooling loads (time = 220 s and 340s). This indicates that the system presents a uniform behavior in this environment temperature range. In Figure 5(e), the path A-B-C represents the mechanical load, while the path C-D represents a decrease of stress in the wire due to the fixation thereof to the structure. Path D-E is related to the 1st heating, wherein there is a stress increase in the wire by spring actuation. Path E-F represents the cyclic response from the 1st cooling to the 2nd cooling.

Figure 6 show the airfoil configurations after heating (Figures 6(a) and (c)) and after cooling (Figures 6(b) and (d)) promoted by the thermomechanical actuation of the SMA wire. As can be seen, there was a maximum deflection of 14 mm (approximately 4°) at the trailing edge end and the deflection of the edge in the cooled stated was of 4 mm (approximately 1°). Figures 6(e) and 6(f) illustrate the von Mises stress in the structure of the airfoil after heating (Figure 6(e)) and after cooling (Figure 6(f)). It can be noted that after heating there was a maximum von Mises stress of 29 MPa in the structure while after cooling there was a maximum von Mises stress of 9 MPa. Hence, the actuation promoted by the SMA wire does not lead to a failure in the airfoil structure.
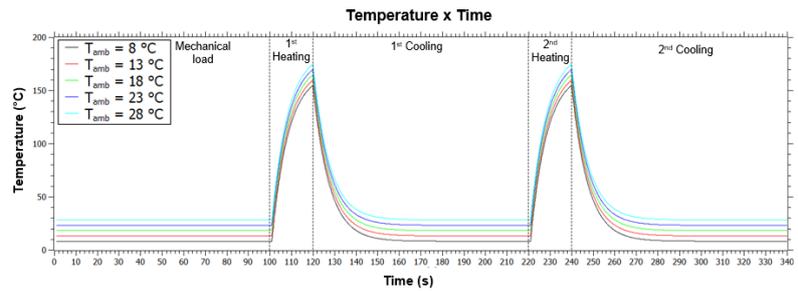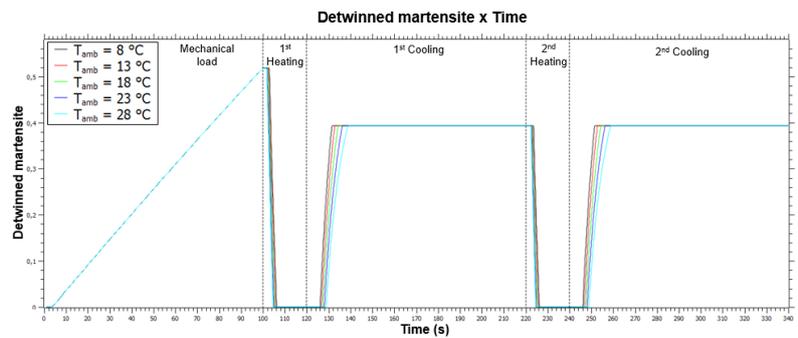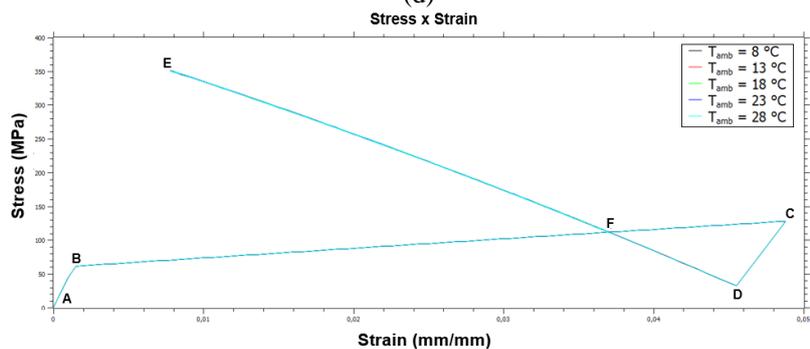
(a)
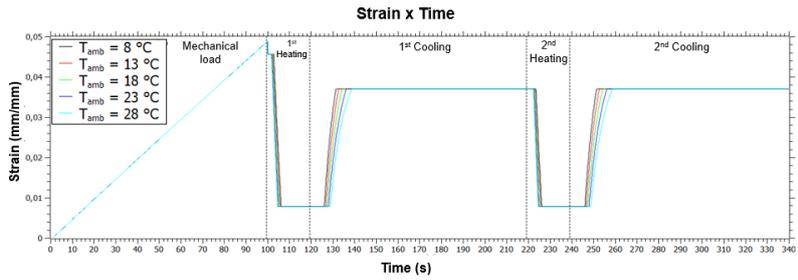
(b)
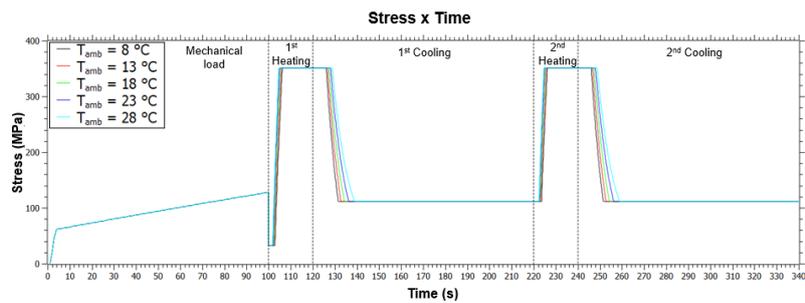
(c)

(d)

(e)

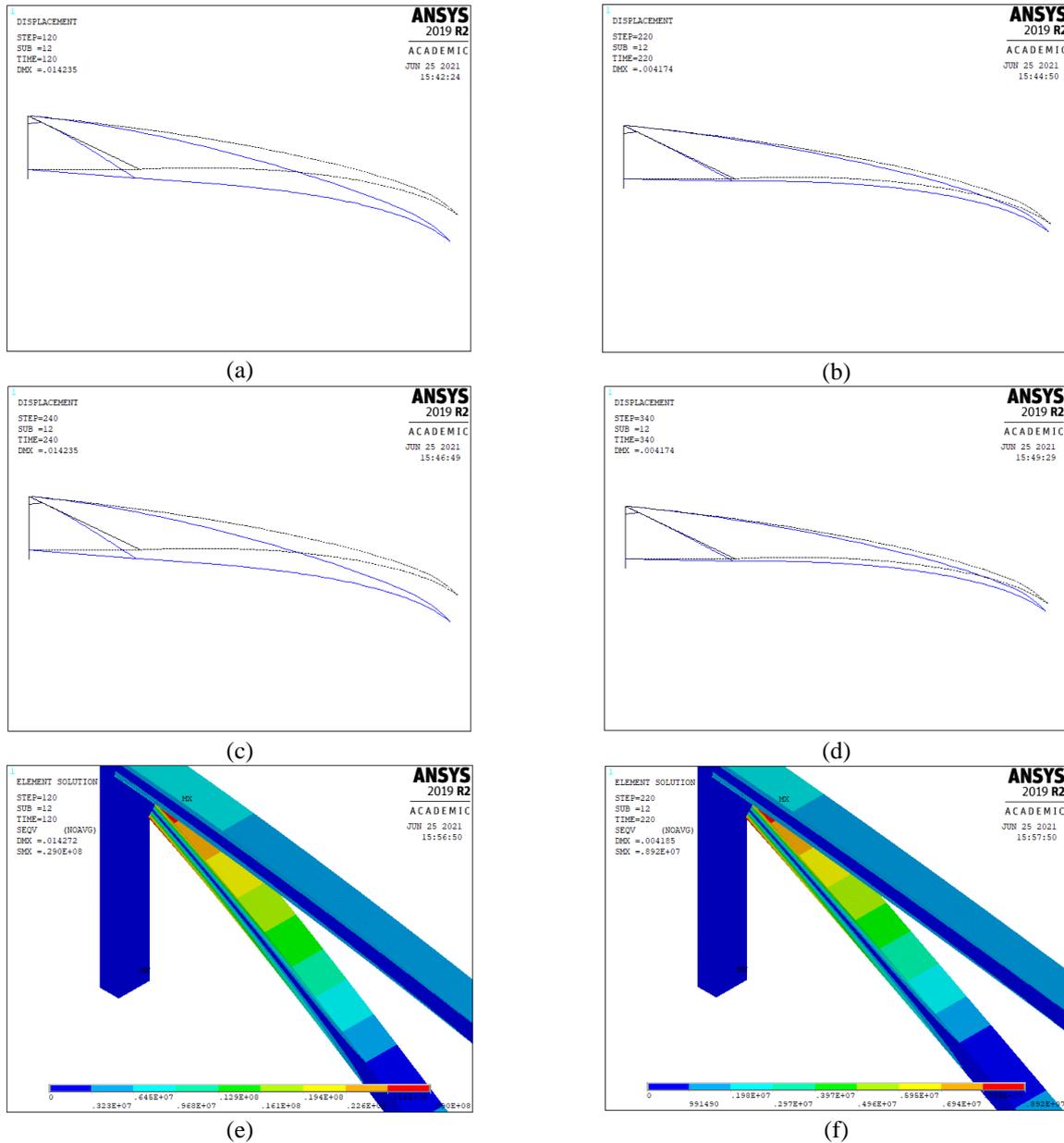Figure 5. Thermomechanical behavior of the SMA wire.

Figure 6. Deformed shape and von Mises Stress.

In order to verify the aerodynamic behavior of the proposed morphing wing, numerical simulations were performed in the XFLR5 software, which solves aerodynamic problems using the XFOIL code developed by Drela (1989) as its computing core and allows the modeling and analysis of airfoils and three-dimensional wings. Figure 7 illustrates the aerodynamic analyzes performed for the wing having a S1223 airfoil. Those simulations were implemented considering angles of attack between 0° and 15° and a velocity of 20 m/s, which are parameters expected for take-off. For an angle of attack of 15°, it can be noted that pressures up to approximately 1700 Pa act in the trailing edge of the wing. This pressure was also included in the finite element analyses as a pressure on the airfoil lines. For better visualization of the aerodynamic load, Figure 7(a) shows a perspective view of the wing while Figure 7(b) illustrates a side view thereof. Moreover, Figures 7(c) illustrates the original S1223 airfoil shape and the airfoil configurations after heating (take-off configuration) and after cooling (cruise configuration). Figures 7(d) and 7(e) show the results of XFLR5 simulations in order to assess the changes in the aerodynamic behavior induced by the SMA actuator. The airfoil simulations were implemented considering angles of attack between 0° and 15° and Mach number equal to 0.06. The Reynolds number range studied was between 200,000 and 400,000. The Mach and Reynolds number values studied are typical of the low Reynolds number regime faced by unmanned aerial vehicles (Sun *et al.*, 2018). As can be noted in Figures 7(d) and 7(e) the take-off and cruise configurations achieve higher maximum lift values than the original S1223 airfoil. For instance, for Re = 200,000, it was verified a maximum lift (C_{lmax}) increase of approximately 5% for the take-off configuration and a lift increase of 1% for the cruise configuration when compared to the original S1223 airfoil. Furthermore, for Re =

200,000 and angle of attack (α) of 0°, it was verified a lift (C_{l0}) increase of approximately 31% for the take-off configuration and a lift increase of 7% for the cruise configuration when compared to the original S1223 airfoil, which can be benefic for maneuvering control.
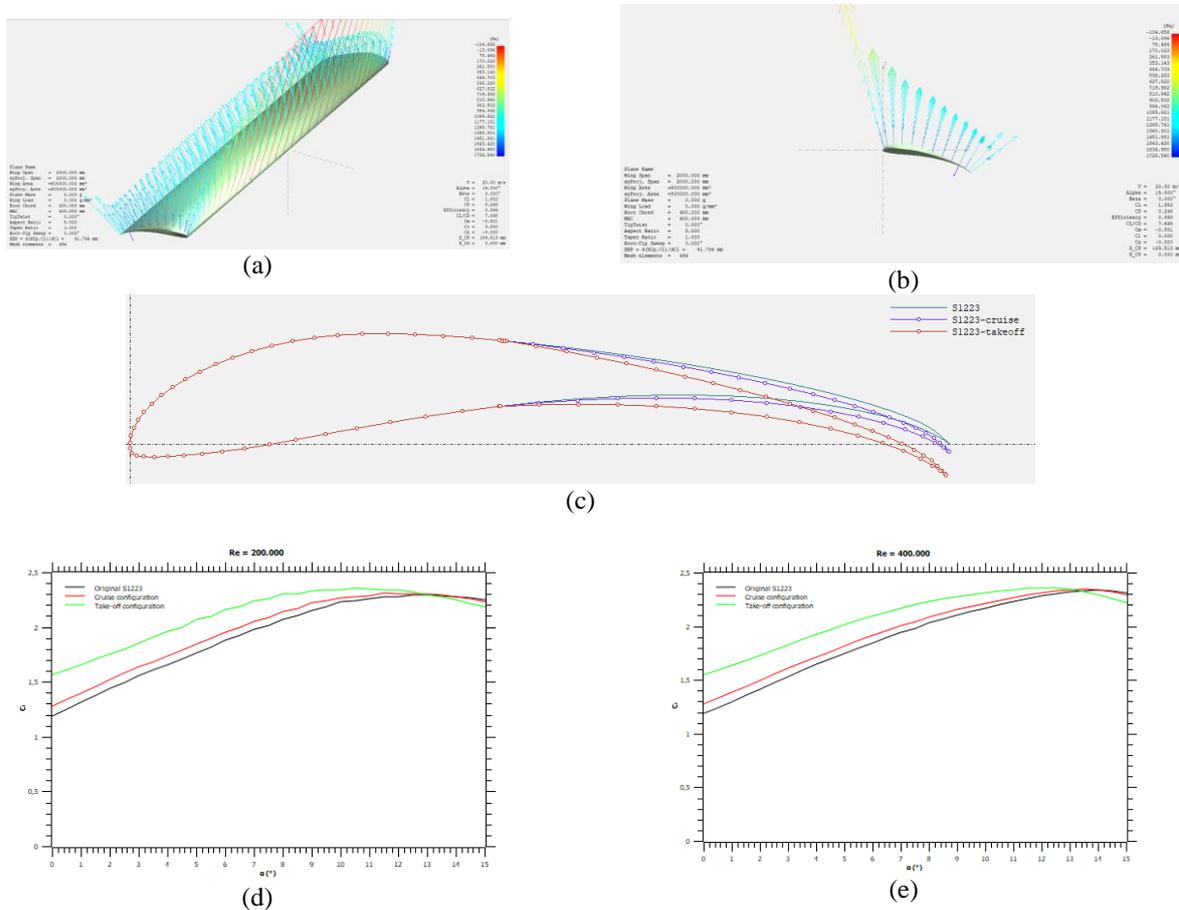

(a)

(b)

(c)

(d)

(e)

Figure 7. XFLR5 wing simulation.

6. CONCLUSION

Bioinspired design of aircrafts has interested scientists and engineers since the early days of aviation. Recently, unmanned aerial vehicle (UAV) projects have used the flight of animals as a basis for structural solutions, since the flight conditions like speed and Reynolds number faced by birds and UAVs are generally similar. In order to achieve modifications in the shape of aircrafts, mainly in their wings, smart materials, such as SMAs, have been extensively used as actuators. This work discloses a morphing wing having variable geometry airfoil sections actuated by SMA elements. The results of numerical simulations using the panel method and the finite element method show that the proposed structure when actuated by the SMA element under a proper thermomechanical loading achieves an increase of approximately 5 % in maximum lift that is useful for take-off phase of flight and an increase of approximately 31% in lift at zero angle of attack that can be advantageous for maneuvering. The proposed methodology can be used to assess the performance of morphing wings for different flight conditions in order to establish optimal geometric configurations.

7. ACKNOWLEDGEMENTS

8. REFERENCES

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