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Morphing structures

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Abstract

This paper presents materials, skins and morphing structures which can be applied in aircraft structures. Ambitious targets for reducing environmental impact in the aviation sector, dictated by international institutions, morphing structures are expected to have potential for achieving the required efficiency increases. There are still open issue related to the design and implementation of deformable structures. A aerodynamic design of a morphing structure is needed. Flexible skins are required in a construction of a morphing wing.

Keywords: morphing, structure, aviation, aircraft, materials, skins

1. Introduction

Aviation is an industrial branch where the newest and most modern materials and technologies are used. Increased passenger and crew comfort by reduction of vibration and noise, increasing amount of structural systems and elements of life, improvements of precise indication and uncovering of infrared and electro-optical sensors on airplanes, are the benefits of using intelligent materials are expected to monitor the state of the construction, detect any kind of damage, and be self-repairing.

Composite materials presently have a wide range of applications. They offer much better benefits comparable to metal alloys, such as reduced weight, increased strength and improved corrosion resistance. However, composite materials react differently to stress and vibrations. Cracking of a metal component is gradual and predictable, while composite materials suffer significant impairment, as a result of accidental damage of an unforeseen and accidental nature. Flexible nature of material and controlled properties are desirable in applications in modern aerospace structures [1], [2].

There is no clear definition of „morphing" structure in the scientist community, but „morphing" structure is or can be identified as structure in which form and surface can be controlled continuously (without any discrete point). As one of the most useful aviation research fields, „morphing" structure had been developed in the earliest times of aviation. Morphing structures enable the change of aerodynamic properties of the lift and steering surfaces during the flight, increasing the efficiency of the flight. The morphing structure can be identified as structure in which form and surface can be controlled continuously [1], [2].

Nowadays, two morphing technology types are considered: discrete morphing, like flaps or retractable landing gears, which are mature technologies, and "continuous morphing", which is a single system that can provide multiple functions in a continuous motion.

For continuous and discrete morphing, technologies have been increasingly evolving during the last decades. Numerous projects are ongoing research. The three main current morphing technologies are shape memory material, actuators and skin morphing. Thanks to flexible materials, rolling motion was controlled with temporary deformations, which was the easiest way of controlling the flight's trajectory. Due to the relative effectiveness of this method, engineers have developed aileron, and later, flaps and slats, which are basically some removable wings parts, to keep control over the plane in a wider speed range [1], [2].

Morphing military systems provide agility, robustness and time responsive action. Shape morphing components such as wings, fuselages and engine inlets, allow aircraft to maintain near optimal operational features and a high level of performance while undergoing predictable or unpredictable, real-time changes in operating conditions. The two-phase DARPA program to develop morphing wing structures to operate over a wide range of airspeeds, up to transonic speeds at high altitude, was completed in early 2006 and transitioned to a brief demonstration phase that saw the design of small flying demonstrator models. Two DARPA-funded contractors designed, manufactured and tested large scale, robotic, morphing wings designs that demonstrated structural integrity and operation in a wind tunnel environment [1].

Morphing structures are largely inspired by biological systems. The flight of birds is a phenomenon that we are all familiar with. Many birds can gracefully vary their flight parameters on a dime simply by changing the shape of their wings (Fig. 1). Structures utilizing smart materials seek to mimic this action in order to revolutionize the idea of human flight. However, unlike birds who use their natural bodies to accomplish morphing during flight, it must overcome new challenges regarding sensing, actuation, and control of a manmade smart structure [2].

Figure 1 – Different wing shapes used by a gliding gull through joint articulation [2]

Early aviation enthusiasts watched birds soar, changing wing shape as they dove and loitered. On the basis of his observations, in 1890, the French aviation pioneer Clement Ader proposed the wing morphing design shown in Fig. 2 [2]. He developed ideas for the future of aviation warfare and described them in 1909.

Figure 2 - Clement Ader's *Eole* – a (non-flying) shape [2]

The central morphing wing challenge is to create design, fabricate and operate effective integrated combinations of deformable wing skins, actuators and mechanisms, structures, and flight controls to provide an aircraft system designer the freedom to deal with future diverse, conflicting vehicle mission capabilities. Wing cover skins must be highly deformable, but still maintain their shape and structural integrity under compression, tension, shear and bending characteristic of aerodynamic and flight loads. New materials being investigated to meet those requirements include shape memory polymers and elastomers, as well as hybrid composites.

In next parts of this paper materials, skins and examples of morphing structures are presented. Smart materials have existed for some time now, but they are still in their infancy with regard to the potential which they carry to revolutionize the field of aviation. Categories of smart materials include shape memory alloys, shape memory polymer, piezo electric material, magnetorheological elastomers. These materials can be made to accomplish useful tasks in the forms of sensing, controlling, and actuation. Information can be transmitted to and from smart material through a multitude of mediums including radiation, magnetism, heat, and by mechanical and chemical means [3], [4], [5], [6].

2. Materials

2.1 Shape memory alloy

In general, only a few specific parts of the plane are made of a shape memory alloy (SMA) depending on where the plane should optimize its morphing more than hinged morphed. They can be used in addition of servo-actuators, pneumatic and piezoelectric actuators. Moreover, a skin such as an elastomer can be placed over the structure (e.g. a wing) which give many possibilities for the technologies to get mixed. SMA can also be used as actuators to modify the wing upper surface.

However, these technologies are not able to get through a certain limit of strain, of width or amplitude, can be heavy, energy-guzzling and are sensitive to hazardous changes in temperature. Another point is that it enables reversible loading and when the voltage is removed, the structure gets back to its original position. Using shape memory alloyed wires to make flexible wings in aircraft to be stretched out or bent down by electric current's heat (Fig. 3). There is no need to reduce weight with large hydraulic lines [7].

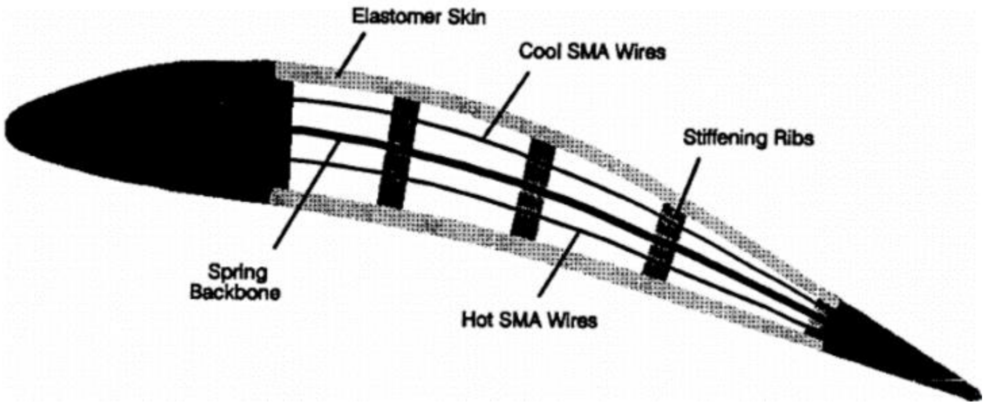

Figure 3 - Shape memory alloy adjustable camber (SMAAC) control surface internal actuator concept [7]

2.2 Shape memory polymer

Shape memory polymers (SMPs) are made to have a flexible skin under airflow (Fig. 4) [8].

Figure 4 - Shape memory polymer wing [8]

Thermomechanical loadings are under control of the wing's wires. SMPs are made to have a mechanic response so to store a deformation and then get its normal shape back under external action such as temperature change. SMPs can convey piezo electricity and so work as an actuator for aircraft morphing. The relation between mechanical deformation and the electric field is linear. So, it is possible to come back to the original shape despite normal polymers where the relation is quadratic. The working properties (Fig. 5.) are explained [5].

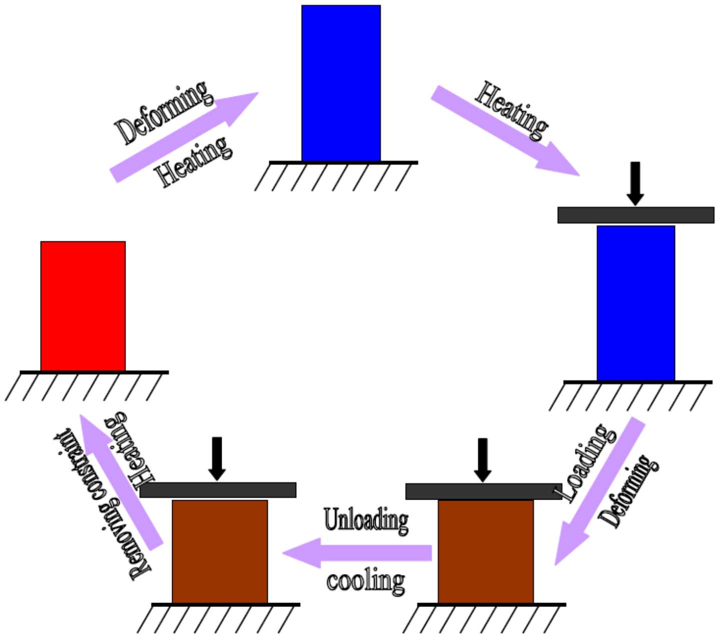

Figure 5 - The typical thermomechanical cycle processing of a SMP/SMPC under compression testing [5]

2.3 Piezo electric material (actuator)

Piezo electric materials can create mechanical stress under electric current and can create electric current if under mechanical stress. Pierre and Jacques Curie discovered piezoelectricity. At the time, Rochelle salt and quartz shown the best piezoelectricity properties. Evolving structures for airplane wings require actuators for big displacements combined with great forces to achieve great mechanic energy transfer.

Also, vibration suppression and form optimization can be reached with piezo electric actuators. For example, see the reduced and internally biased oxide wafer piezo electric actuator and its link with SMA. To the best knowledge of authors [9], the earliest work with this regard traces back to where a two-level optimization procedure was developed for the design of a flexible structure system with a piezo-ceramic actuator.

The case of actuators for aircraft is particularly important for the wing morphing and the control over the aircraft form. Nowadays, piezoelectric materials are lead-free thanks to directives on environmental concern. Today, no piezoelectric actuator has sufficiently high mechanical response than what is needed for morphing any aircraft. Ongoing research is trying to overcome such limitations [9].

2.4 Magnetorheological elastomers

Magnetorheological elastomers (MREs) are composed of a non-magnetic polymer matrix with randomly dispersed ferromagnetic particles. Thanks to a specially designed structure, the magnetic particles cannot move freely within the matrix. Therefore, there is no sedimentation. Magnetic field application stimulates a non-linear and reversible change of some of the properties. The limited movement of particles results in a quicker response to a magnetic field than in MR fluids. Magnetorheological elastomers work in the post-yield region, which differentiates them from MR fluids. There are two main types of MR elastomers: polarized elastomers (anisotropic) which have a strictly organized internal structure and isotropic elastomers [10]. The difference between these two kinds of MR elastomers, an external magnetic field is applied. Fig. 6 presents SEM microstructure of MRE revealed on a surface of sample containing CIP HS.

The rheology of MR elastomer changes following the magnetic field applied. Smart materials are not only used in morphing in-plane structure, but smart skins are also used in morphing out-of-plane structure. Magnetorheological elastomers may be used as such a skin. Skins are presented in the next chapter.

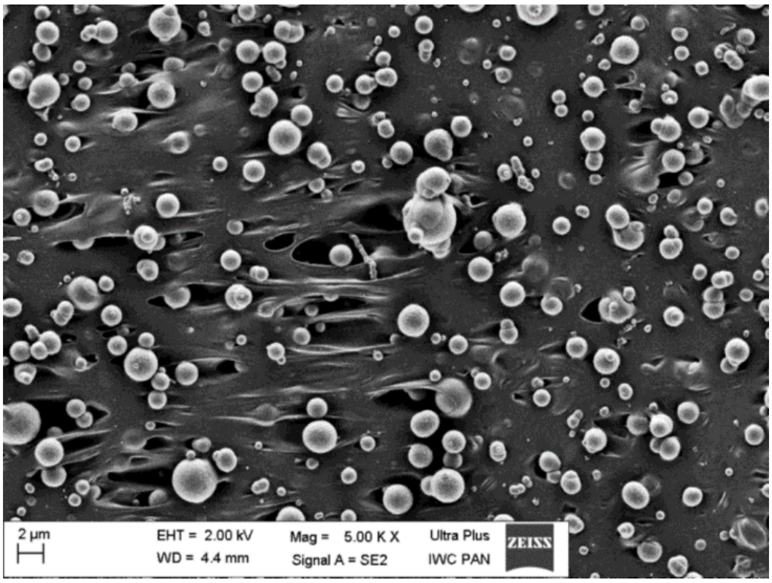

Figure 6 – SEM microstructure of MRE revealed on a surface of sample containing CIP HS

3. SKINS

3.1 Description and properties of smart skins

Since the wing is deformable thanks to the morphing structure, its wing surface is variable, so there is a need to have a cover which follow the movement and the deformation of its support.
In the case of a plane wing, the smart skin have to be elastic but remain useful, that means that at any time, the smart skin have to react as a normal cover on a normal wing: it has to transmit the aerodynamic loads to its support (the wing structure), and not be deformed by it [6].
Plus, a smart skin have to be anisotropic: it should not respond equally at the same strain applying at different direction on the materials. Indeed, to control the general wing form, and so to manage the aerodynamic load, the skin shouldn't move at similar manner to an extern stress, as a pressure, than a wing strain due to morphing structure.
Furthermore, the skin must have the capacity to sustain elastic deformation although never be in plastic deformation: it means that any transformation of the smart skin should be reversible.

3.2. Geometry of a smart skin

Different smart skin technologies exist, each are formed differently at macroscopic scale. All of them meet the requirements and properties needed, has defined previously. In this part, three of them are presented: the corrugation geometry model, the honeycomb reinforced elastomer model and the magnetic material skin model [6].

3.2.1. Corrugation geometry model

This geometry allow to 'stock' material which is use to extend the skin. This layover is perpendicular to the propagation direction of the skin, and is negligible before the characteristically length of the covered area of the wing.
To control and optimize this method, [11] propose a model with a trapezoidal geometry (Fig. 7).

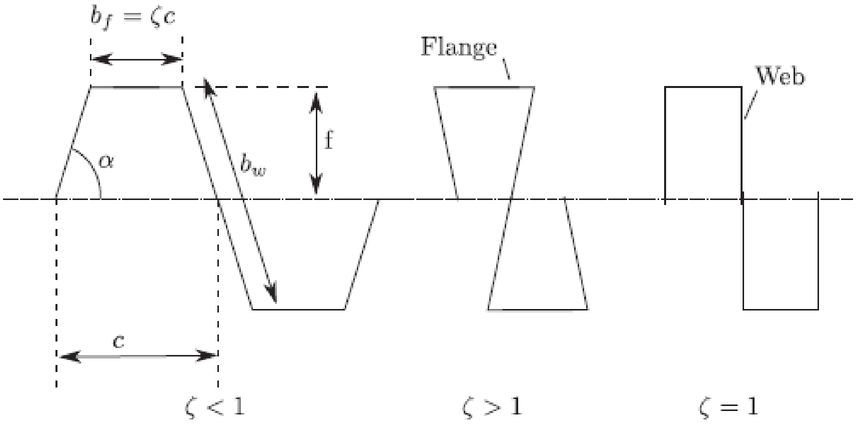

Figure 7 - Corrugation geometry [11]

By modifying the length of b_f, it modifies the form of the corrugation: trapezoidal, re-entrant or square. For the re-entrant case, b_f have to be strictly inferior to 2×c, to avoid overlapping.

3.2.2. Honeycomb reinforced elastomer

Specific materials, such as elastomer, have natural properties in adequacy with smart skins: it can't suffer from plastic deformation, it is elastic, and resistant. But smart skins can't be exclusively made of elastomer materials, it will be too elastic, and will not integrally transfer aerodynamics load to its supports.
To fortify them, we can use a honeycomb structure (Fig. 8), which will rigidify the whole structure. To implement this technique, a 'sandwich' can be made, with the honeycomb in the center of two elastomer layer [6].

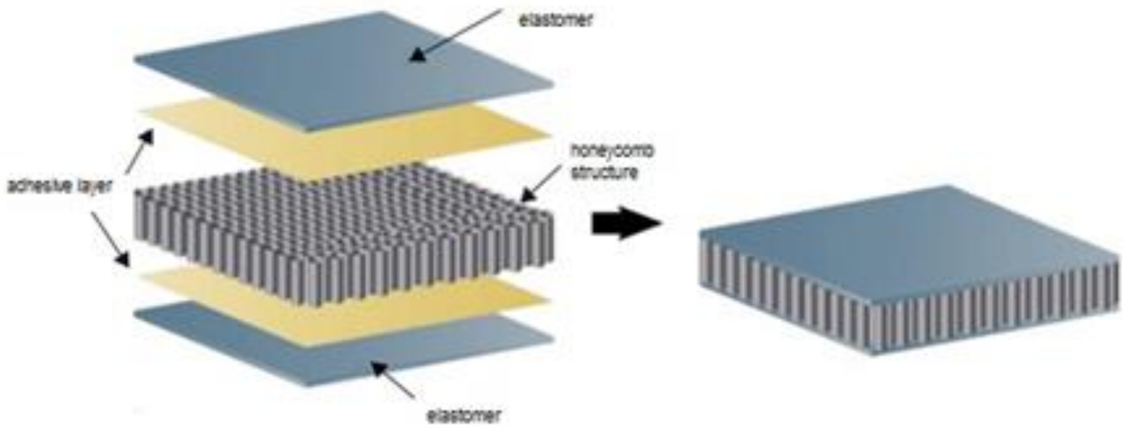

Figure 8 - Sandwich of elastomer [6]

This technical solution has the disadvantage to make a larger depth morphing skin, and to wear down over time.
Another method consist to fill the honeycomb core with elastomer. The elastomer is weld with the honeycomb structure, which increase the adhesion force while eliminating local deformation.
The depth of the skin is reduced compared to the first method, but it conserves the same bending stiffness.
Finally, this method is easier to implement industrially, and is stronger over time.

3.2.3. Skin made by a magnetorheological elastomer

A magnetorheological material (a smart skin) is a new development for morphing aircraft concepts. The primary phase of the morphing skin development the magnetorheological material was fabricated that would make up the skin or face sheet. Fig. 9 shows a view of a new smart material. Elastomeric materials are ideal candidates for a smart skin. In morphing applications, where large shape changes are expected, the design of a suitable skin is a huge challenge and a key issue. The skin must be soft enough to allow shape changes but at the same time it must be stiff enough to withstand the aerodynamics loads and maintain the required shape/ profile. This requires thorough trade-off design studies between the required depends on the loading scenario and the desired change in shape (one-dimensional or multi-dimensional) [12].

Magnetic investigations of a magnetorheological smart skin were performed on the LAKESHORE vibrating sample magnetometer (www.lakeshore.com). The range of a magnetic field was between 0 – 1600 [kA/m] (2 [T]). Presented results of experiments (Fig. 10) prove, that magnetic properties of a magnetorheological skin can be controlled [12].

Results obtained from experimental research carried out for the magnetorheological material (smart skin) revealed, that there is a considerable influence of a magnetic field on properties of a smart skin. Because these changes are entirely reversible, it is possible to use a magnetorheological material as “intelligent” material - a part of a morphing structure [12].

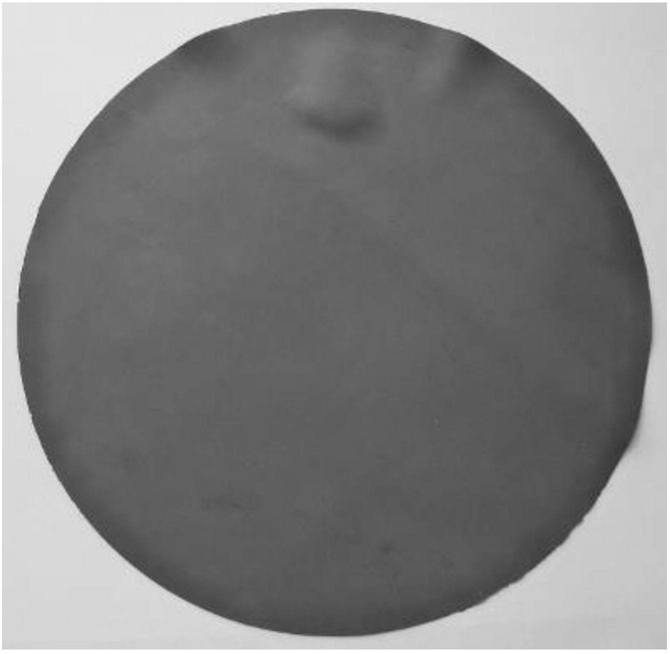

Figure 9 - View of a smart skin [12]

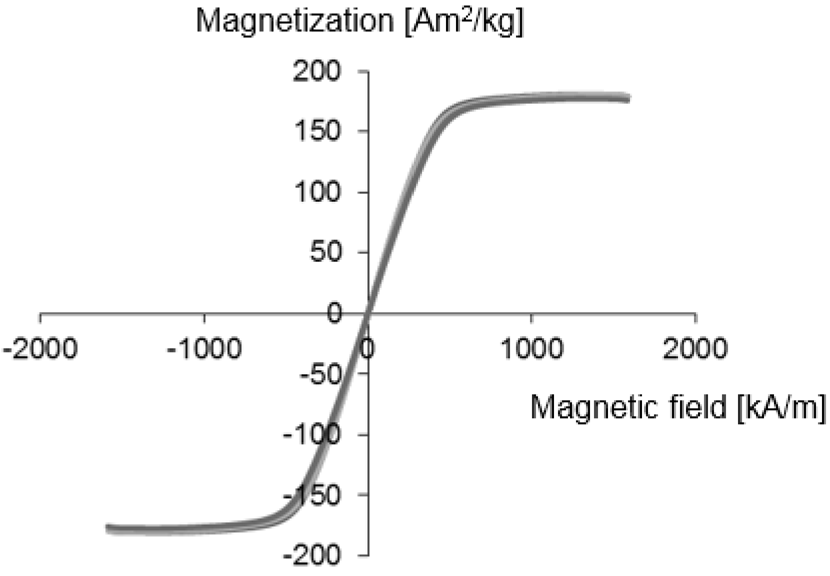

Figure 10 - Results of magnetic investigations of a smart skin [12]

4. Morphing Structures

4.1. Flap which serves and morphing concepts

The materials and mechanisms employed should correlate with the range of deformation desired. Corrugated structures, segmented structures, reinforced elastomers, and flexible matrix composite tubes embedded in a low modulus binder are all viable choices of material for small morphing deformations. Figure 11 represents a design concept where the ribs are removed from the wing and replaced by additional thin spars. This is called the belt rib concept, and it would allow small deformations to change camber dimension. On the other hand, large wing changes should be accomplished by deployable structures so as to minimize the induced stress when morphing is performed [2], [8]. Figure 12 shows a flap which serves as an example of a component that if designed to be composed of smart materials, should utilize a deployable structure mechanism.

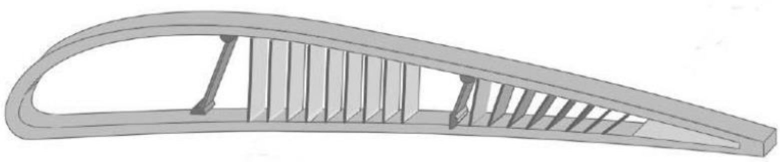

Figure 11 – Belt rib concept [8]

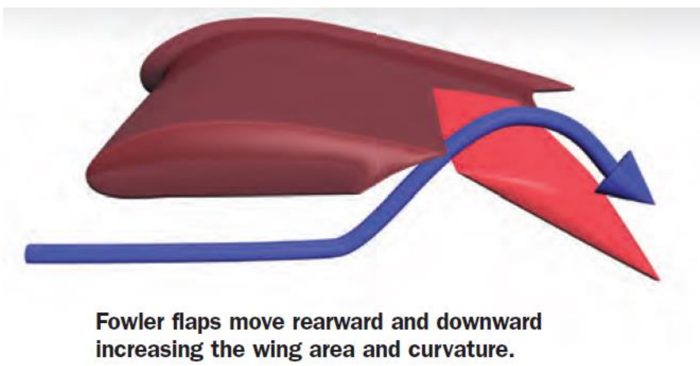

Figure 12 – Flap which serves [8]

A major issue which must be faced in the development of a morphing structure is the need for an outside skin which is flexible enough to bend and contort to the changes in wing shape while simultaneously being rigid enough to transmit aerodynamic loads to the underlying structure.

A proposed solution is carrying out a procedure to develop a curvilinear composite structure which fits these design requirements. Tests have been performed on a variable stiffness skin which can be optimized for high-lift devices. This variable stiffness skin is achieved by a spatial fiber angle and skin thickness variation. The tailored stiffness distribution beneficially influences the structural deformation. The ideal skin structure can be designed by having the actuation loads as part of the design variables from the onset of design. The actuation loads can be minimized while the skin is optimized such that the combination skin/actuation gives the best performance with respect to the objective function. The results indicate a favorable material with low in-plane stiffness and high out-of-plane bending stiffness [9, 10, 11].

Morphing will allow aircraft to change wing area, sweep angle, and span during flight. Several reputable aircraft have already been produced with smart skin technology through DARPA (Defense Advanced Research Projects Agency). Lockheed Martin has performed research on a “folding wing concept” which works by using shape memory alloys to fold the wings and thereby achieve variable wing span (Figure 13). In this concept, the skin material is manufactured from a shape-memory polymer that softens and morphs within seconds after being heated. Heating is performed by small, flexible heaters embedded into the material in the form of layers. When the required shape change is achieved, heating is stopped, which fixes the wing shape. NextGen was able to develop an aircraft with both variable sweep and chord dimensions by the use of a hydraulically actuated truss structure (Figure 14). The skin material is silicon reinforced by metal which produces morphing. Variable sweep design is the most successful morphing application of aircraft today [1], [3].

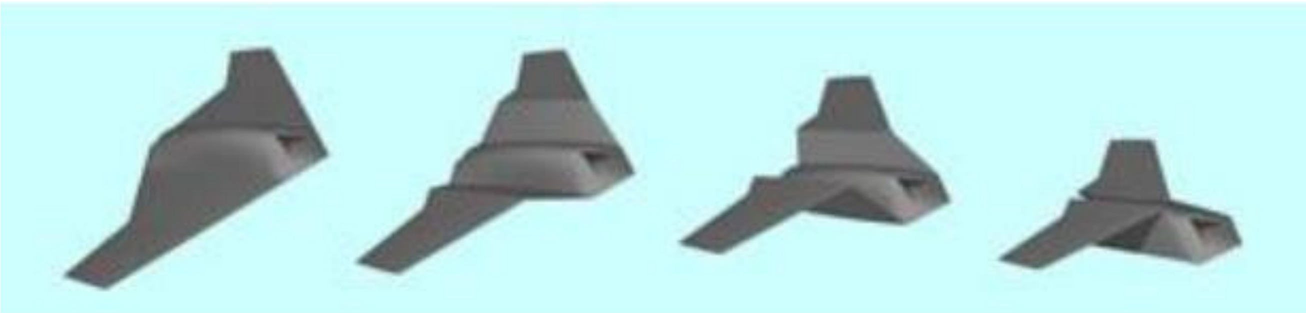

Figure 13 - Lockheed – Martin’s “folding-wing” concept [1]

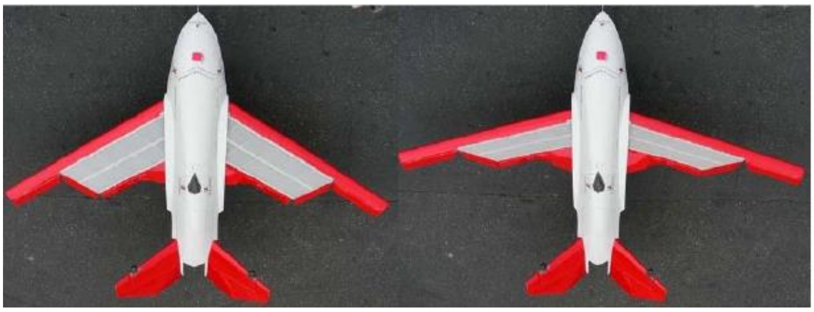

Figure 14 - Nextgen’s “variable-chord, variable-sweep” concept [1]

Trapani [13] carried out a study to enhance the directional stability and controllability of an aircraft vertical tail wing. This mechanism is called a gapless and rudderless aeroelastic fin (GRAF). It proved that a composite seamless structure could be designed to give similar characteristics as a conventional one, and even provide more stability. This test was on a tail-wing, but the concept could be extended to other airplane airfoils.

Active truss structures with morphing capabilities are another option. The passive components of the wing can be replaced by an active truss controlled by linear actuators. An actuation mechanism consisting of a stepper motor with a self-locking lead screw pitch has demonstrated the advantage of no constant power source being required to hold the system at a constant position [13].

The desired morphing can also be accomplished by compliant structures. A compliant structure is a mechanism with no joints that takes advantage of the elasticity of material to produce a desired functionality. A compliant system consists of actuators and sensors integrated within the compliant structure for transmission. The material is arranged within the compliant mechanism so that compliance is distributed through small strains to produce large deformations. This design minimizes stress concentrations and fatigue. Just as designs in nature are strong but compliant, so are bio-inspired complaint mechanisms [13].

4.2. Aviation structure with a magnetorheological elastomer

In the patent [14] an airfoil with a variable shape was described. It has an elastic coating made from an active material (magnetorheological elastomer) allowing to change the aerodynamic characteristics of an aircraft wing or a rotary blade during flight. In this solution presented in fig. 15, a thin layer of magnetorheological elastomer (2) was placed on the upper side of the reversed wing (3). Magnets (1) were placed underneath this surface (12) in order to generate a strong magnetic field 0.5T that would attract the MR elastomer (2) and therefore change the overall profile of the wing. One end of the MR elastomer (2) is connected to a shaft (4), second end is fixed to the wing (3). A special mechanism (8) moves and controls the thin layer of magnetorheological elastomer in this structure [14].

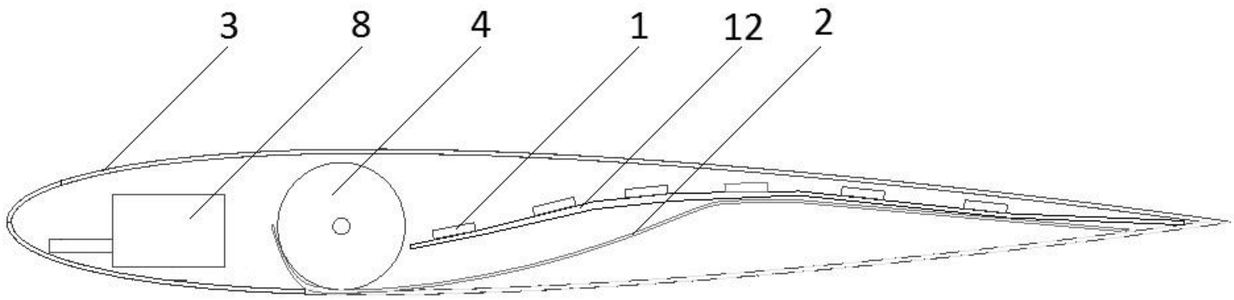

Figure 15 - Schematic view of the morphing structure with a magnetorheological elastomer [14]

Investigations of such a structure are performed in the Institute of Aviation. For the purpose of this investigations an E214 aerofoil has been selected. The aerodynamic characteristic of this particular aerofoil has been already tested and documented in [15].

5. Conclusions

Morphing structures plays a key role in aviation research and development. Implementations of new smart materials and new smart skins, it becomes more and more realistic to get a nature-like plane, optimizing its energy consumption to optimized shape structure where we are used to brute-force take off and navigation.

The new aviation structure with a magnetorheological elastomer was presented. The surface of the wing profile is modified by changes of the magnetorheological elastomer. The proposed morphing structure was designed and performed in the Łukaszewicz Research Network – Institute of Aviation.

The design of most modern fixed-wing aircraft has devolved into very stiff structures which employ the use of rigid devices such as flaps, slats, elevators, rudders, etc. to control flight. Although these components perform all the necessary maneuvers to accomplish successful flight, they are an inherent compromise which is only efficient in one realm of flight conditions. It has become clear that efficiency can be achieved across a wider spectrum of flight parameters by incorporating morphing technology into the design of aircraft. Morphing structures have the potential to increase aerodynamic efficiency, eliminate complex and heavy high lift devices and mechanisms, eliminate complex conventional control surfaces, reduce aerodynamic noise, reduce fuel consumption, control vibration and flutter, effectively carry out various flight maneuvers which previously would have been unconceivable.

The concept of a morphing aircraft is no new idea. The development of such aircraft has been advancing at a slow pace due to the immense complexity which is involved in controlling morphing structures. In order for a morphing system to be appropriately applied to an aircraft, it needs to be directly involved from the very beginning of the design process. The morphing structure must be fully integrated into the entire aircraft since many sensors and actuators will be required to accomplish a smooth morphing action.

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7. Copyright Statement

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