Development of dielectric elastomeric actuators for morphing wings

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Abstract: *In the last decades, wing morphing structures have aroused great interest due to their capability to improve the aerodynamic efficiency of modern aircraft. DE actuators, also known as “artificial muscles” due to their ability to exhibit large actuation strains at high voltages, are suitable candidates for morphing applications. This paper focuses on the research and development of miniature dielectric elastomeric actuators for variable-thickness morphing wings. A conical elastomeric actuation configuration has been proposed, consisting of a VHB4910 dielectric membrane preloaded with a spring mechanism and constrained to a rigid circular ring. The mini-actuators are developed to be fixed in an actuation array, mounted to the wing skin. This new electromechanical actuation system is designed to be integrated on thin airfoil wings, where conventional morphing structures cannot be used, because of restricted mass and space requirements. By controlling the thickness distribution using the proposed actuators, we may be able to maintain and delay the location of the laminar-turbulent transit towards the trailing edge, promoting laminar flow over the wing surface. Experimental models and prototypes will be developed in the next phase of the research project for further investigations.*

Key Words: *morphing wings, dielectric elastomer actuators, graphite electrodes, conical preloading configuration, actuation array, environmental perturbations*

1. INTRODUCTION

Due to the high carbon footprint of the aviation sector, new technologies are currently researched to improve the energy efficiency and sustainability of modern aircraft. Morphing wings can improve aerodynamic efficiency by optimizing the shape of the airfoil according to flight conditions. A major challenge in the design of wing morphing structures is the development of the actuation system. Conventional actuators are often too heavy and occupy a large amount of space, so the interest in developing new lightweight morphing actuators has increased in the last decade. Due to the recent advances in electroactive polymer research, a new promising actuation solution has emerged: the dielectric elastomer. Dielectric elastomers (D.E.), also known as “artificial muscles” in the scientific literature, are electroactive polymeric materials that have the ability to transform electrical energy into mechanical work. Dielectric elastomer actuators are suitable candidates for morphing applications due to their many advantages over conventional actuators, such as high actuation strains and lightweight structures. However, designing and developing morphing dielectric elastomer actuators can be challenging because of the complex behavior of the material. The objective of this paper is to highlight the design challenges of morphing dielectric elastomer actuators and propose a new miniature dielectric elastomer actuator for variable-thickness morphing structures that can be mounted on thin airfoil wings where conventional actuators cannot be used because of limited space requirements.

2. THEORETICAL ASPECTS OF DIELECTRIC ELASTOMERS

Dielectric elastomers work as electrostatic actuators. When electrical field is applied on the surface of the material, electrostatic forces act between the electrodes and compress the membrane.

The electro-mechanical behavior of the dielectric elastomer material can be theoretically studied using a thermodynamic model.

Considering the material as an ideal elastic body and neglecting the dissipative energy (D), we can write the balance between the total work rate (δW) and the Helmholtz free energy (ψ) as [1]:

$$dD = \delta W - \delta\psi = 0 \tag{1}$$

The total work produced by the elastic material can be written as the sum between the mechanical work and the electric field work. We define the force needed to deform the DE material as (P); the distance between the electrodes (l); the electrical flux (ϕ) and the variation of charge (δq) [2]:

$$\delta W = P\delta l + \phi\delta q = \delta\psi \tag{2}$$

$$\delta\psi = \frac{\partial\psi}{\partial l}\delta l + \frac{\partial\psi}{\partial q}\delta q \tag{3}$$

From equation (3), the equations of state of the dielectric elastomer can be expressed as:

$$P = \frac{\partial\psi(\mathrm{l,q})}{\partial l} \tag{4}$$

$$\phi = \frac{\partial\psi(\mathrm{l,q})}{\partial q} \tag{5}$$

Using the equations of state, we can determine the relationship between the deformation force (P) and the applied charge (q) according to the electrode surface (A):

$$P = \frac{q^2}{2\varepsilon_0\varepsilon_r A} \tag{6}$$

Knowing that the electric field intensity is: $E = \frac{q}{\varepsilon_0\varepsilon_r A}$, we can write the resulting deformation stress (σ) (also known as “Maxwell stress”) as:

$$\sigma = \frac{1}{2}\varepsilon_0\varepsilon_r E^2 \tag{7}$$

where: ε_0- vacuum dielectric permittivity; ε_r- relative dielectric constant of the elastomer and E- electrical field intensity.

3. THE VISCOELASTIC BEHAVIOR OF ELASTOMERS

Viscoelasticity represents the molecular mechanism of elastomer materials to exhibit elastic and viscous forces when undergoing deformation.

The viscoelastic properties of the elastomer depend on the chemical structure of the material and are very important to consider in the design process of a dielectric elastomer actuator.

Due to viscoelasticity, the mechanical properties of elastomer materials are temperature-dependent.

Without a clear understanding of the viscoelastic behavior of the dielectric elastomer, the long-term performance of the actuator cannot be predicted.

An important material parameter of the elastomer material is the “glass transition temperature” denoted by T_g.

With a temperature under the glass transition temperature, the material has a “glassy” behavior with high stiffness and low tensile strength. As the temperature increases above T_g, the elastic modulus decreases, and the material becomes more flexible, allowing higher recoverable deformations [3].

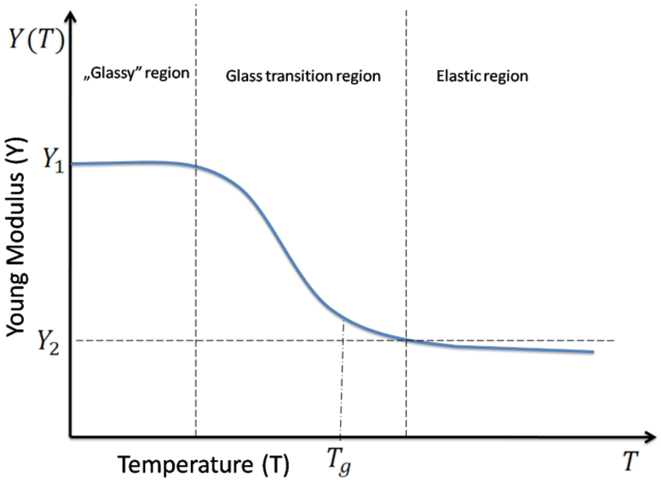

Fig. 1 – The temperature dependency of the elastic modulus for elastomers

4. ENVIRONMENTAL PERTURBATIONS ON THE PERFORMANCE OF MORPHING D.E. ACTUATORS

Dielectric elastomers are heavily influenced by external environmental conditions, such as ambient temperature, humidity, and atmospheric pressure. For morphing applications, dielectric elastomer actuators need to work efficiently at extreme environmental conditions like any other flight component.

Technical solutions need to be found to improve the operating range of the actuators and ensure maximal operational performances.

For the main environmental perturbations, possible solutions have been proposed in the table below (Table 1).

Table 1. – The environmental perturbations and proposed solutions for morphing dielectric elastomer actuators

Perturbation	**The influence onto the actuator**	**Possible solutions**
Temperature variation (-60°C / 50°C)	- The variation of the elastic modulus of the DE material due to viscoelasticity	- Insulating the actuator and designing a thermostatic system to maintain a stable and optimum temperature. - Pre-stretching the elastomer to reduce the sensitivity to the temperature variations [4]
High humidity	- Increases the wear and reduces the reliability of the actuators - Reduces the dielectric breakdown strength of the DE material [5]	- Using stainless materials (for the preloading mechanism) - Placing the actuators in a hermetically sealed environment with low humidity
Atmospheric pressure variation	- Displacement errors	- Placing the actuators in a hermetically sealed environment

5. SELECTION OF DIELECTRIC ELASTOMERS

For wing morphing applications, we require a highly reliable material with low stiffness and high dielectric constant and breakdown strength. As we discussed previously, for high morphing actuation performances, the dielectric elastomer material requires a glass transition temperature below the lowest temperature that can be reached in the stratosphere (-60°C).

Two dielectric-elastomer material types have been proposed in this paper for morphing D.E. actuators: acrylic elastomers and silicone rubbers.

Silicone rubbers usually have a low glass transition temperature and high dielectric breakdown strength, offering a wide operating range and better reliability against environmental perturbations. A silicone elastomer that can be used for dielectric actuators is the Sylgard 186 elastomer, manufactured by Dow Corning.

While acrylic elastomers can offer large strains, the performances are heavily influenced by the highly viscoelastic properties. One of the most used acrylic elastomers for dielectric actuators is the commercially available VHB4910 elastomer manufactured by 3M. To be used for morphing applications, the VHB4910 elastomer needs to be thermally insulated in the actuator due to the high glass transition temperature (see Table 2.)

The values range of the electrical and mechanical properties for the VHB4910 material and the Sylgard 186 silicone elastomer is presented in the comparative table below (Table 2):

Table 2. – Material properties for the VHB4910 and Sylgard 186 elastomers

Property	**VHB4910** [6]	**Sylgard 186 (Silicone elastomer)** [7]
Dielectric constant	4.7 [8]	3.4
Dielectric breakdown strength (E_b)	24.8 kV/mm	87 kV/mm

Youngs modulus (*Y*)	2 MPa	1.2MPa
Poisson Ratio	0.5	0.5
Glass transition temperature (T_g)	-40°C [9]	-55°C [10]

To better visualize the properties of the proposed materials, the relationship between the electrical field intensity and the mechanical stress and strain have been plotted in Fig. 2 and Fig. 3:

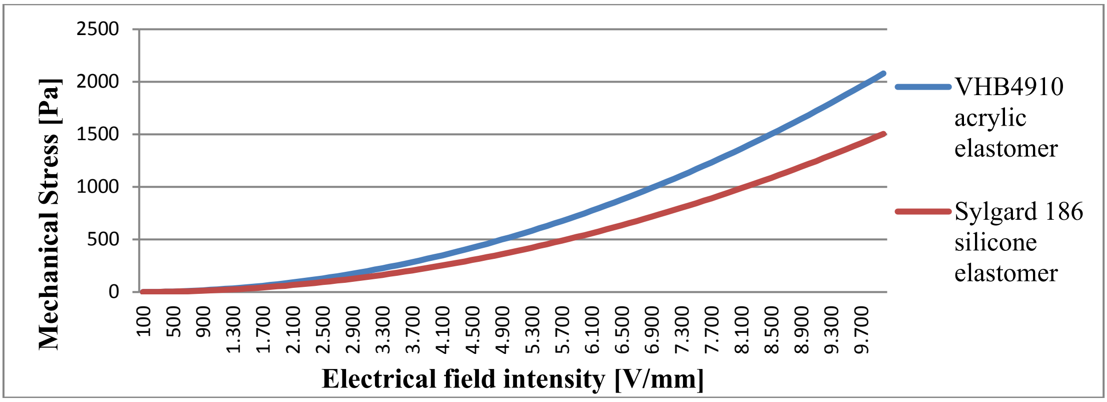

Fig. 2 – The stress – electrical field intensity curve for the VHB4910 and Sylgard 186 elastomer

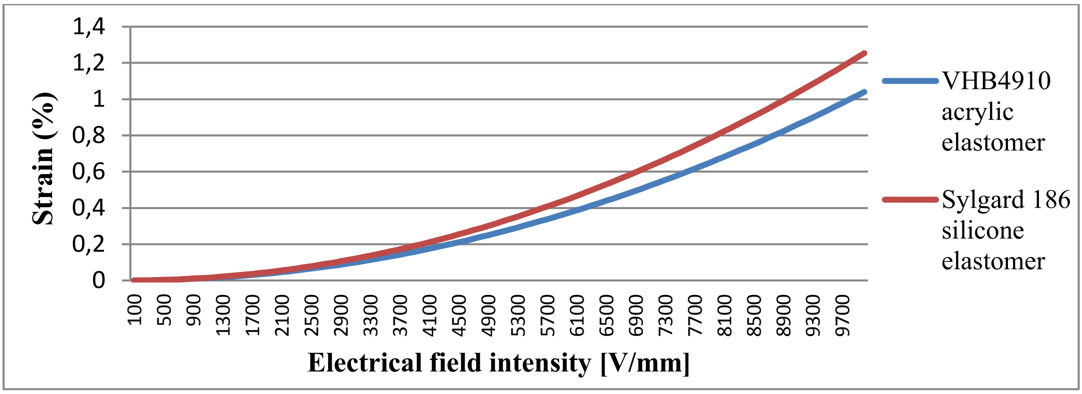

Fig. 3 – The strain – electrical field intensity curve for the VHB4910 and Sylgard 186 elastomer

6. CONICAL PRELOADING CONFIGURATION

Preloading or pre-stretching the material has proven to be an effective way to improve the performance and efficiency of dielectric elastomer actuators. Pre-stretching the elastomer increases the stiffness of the membrane and it turned out to be a solution for improving the dielectric breakdown strength of the elastomer [11]. For the VHB4910 material, it has been empirically demonstrated in the scientific literature by Huang (2012) [11] that the dielectric breakdown strength depends on the biaxial pre-stretching ratio, following the equation: $E_b = 51{t_h}^{-0.25}\lambda^{0.63}$, where t_h represents the membrane thickness, and λ represents the biaxial stretch applied in a preloading configuration. Also, in recent studies [4], preloading has been shown to improve the temperature sensitivity of highly viscoelastic materials, such as the previously discussed acrylic elastomer. For morphing actuation, we propose in this paper a conical preloading configuration for the dielectric elastomer membrane. A conical configuration can offer large vertical out-of-plane deformations and can be easily implemented

and mounted under the wing skin. The main drawback of this configuration is the design challenges and difficulties due to the non-homogenous preloading stress and strain.
The schematic of the conical preloading mechanism is presented in the figure below (Fig. 4):

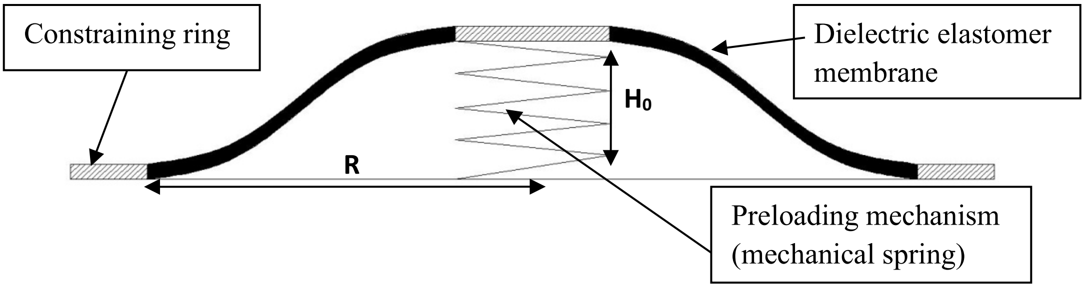

Fig. 4 – The conical preloading configuration in passive state (un-actuated)

7. FINITE ELEMENT ANALYSIS OF THE PRELOADING CONFIGURATION

To better understand the stress and strain levels in the preloaded elastomer membrane, a static finite element analysis has been performed using ANSYS Mechanical. This computational analysis represents the first step towards the design of a preliminary experimental model. Two case studies have been considered in the FEA analysis. In the first case study, the preloading stress and strain have been analyzed for a 10mm initial vertical displacement (H_0). For the second case study, a 15mm vertical displacement has been considered. The proposed geometrical parameters for the conical dielectric elastomer actuator CAD model are presented in table 3.

Table 3. – The geometrical parameters for the studied geometry model

Geometrical parameters	**Dimensions**
Diameter of the spring (d)	10mm
Diameter for the holding ring (D)	50mm
Initial vertical displacement (H_0)	10mm (Case study1) / 15mm (Case study 2)
Initial Membrane thickness (t_h)	1mm
Constraining ring thickness	5mm

The proposed geometrical parameters of the actuator are presented in figure 5.

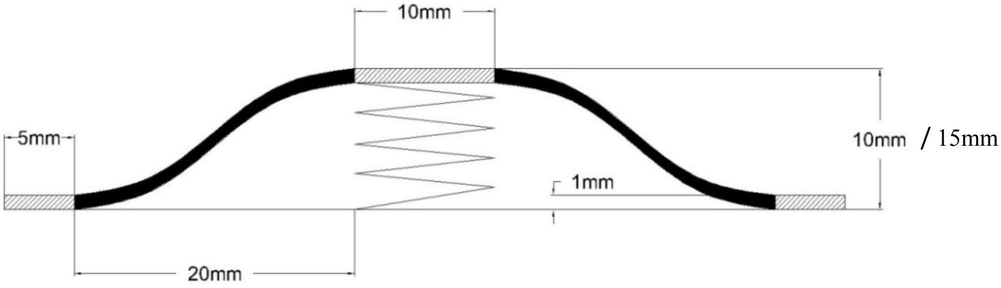

Fig. 5 – The geometrical parameters of the studied conical FEA model

Due to the complex deformation behavior of elastomers, a Neo-Hookean hyperelastic material model has been used for the FEA. In contrast with linear elasticity, the stress/strain curve of Neo-Hookean materials is nonlinear and depends on the initial shear modulus. Unlike other hyperelastic models, the Neo-Hookean model considers the material as an ideal elastic body and does not take into account the dissipative energy [12]. The Neo-Hookean model is based on the statistical thermodynamics of elastomer macro-molecular chains.

The stress/strain relationship for the VHB4910 acrylic elastomer (considering an initial shear modulus of 0.5MPa) can be seen in figure 6:

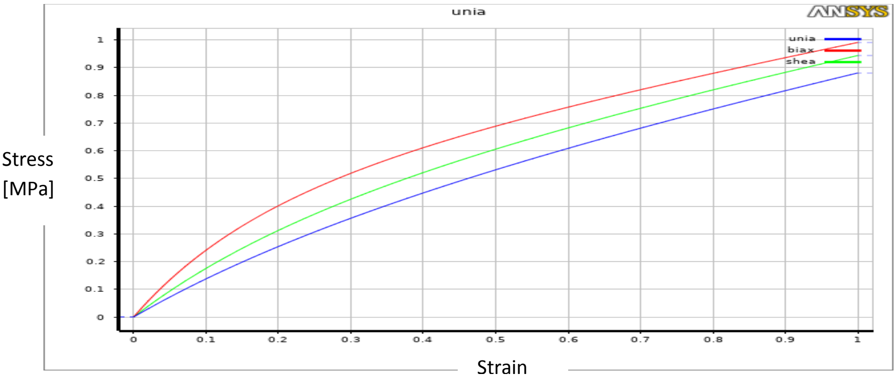

Fig. 6 – The stress-strain relationship according to the Neo-Hookean model for the VHB4910 material

8. INTERPRETATION OF FEA RESULTS

The final geometry resulted for both case studies after applying the boundary conditions and meshing the geometrical model are presented in the images below:

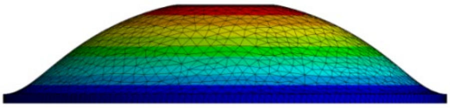

Fig. 7 – The final geometry of the preloading configuration with a 10mm vertical displacement

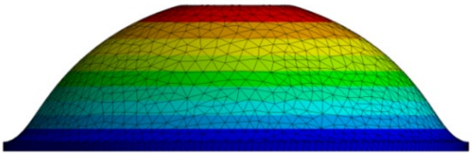

Fig. 8 – The final geometry of the preloading configuration with a 15mm vertical displacement

For the preloading stress distribution in the elastomer membrane, the following results have been obtained (Fig. 9):

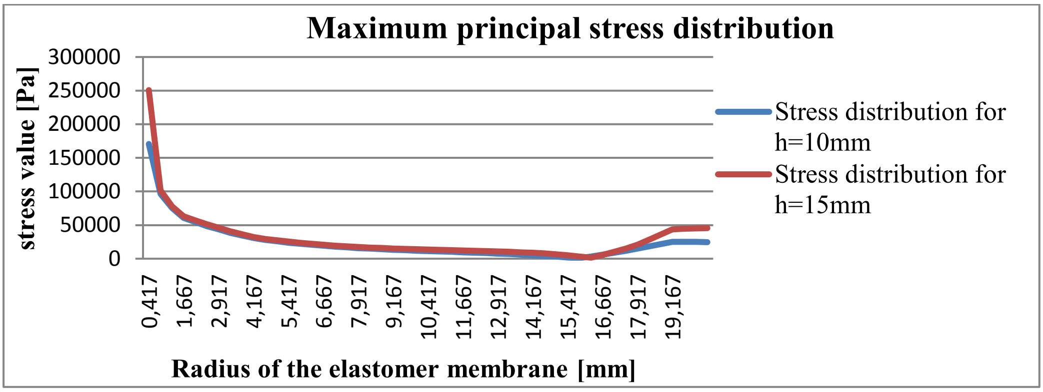

Fig. 9 – Preloading stress distribution in the elastomer membrane

As shown in figure 9, the maximum stress in the membrane is reached at the center of the membrane, where the preloading force is applied. The stress abruptly decreases with the radius and reaches a point where the stress distribution follows a linear decrease. The minimum stress level for both case studies is reached at a 16 mm radius.

In the proximity of the holding ring (16 mm – 20 mm), we can observe the increase of the stress level to a steady value. For a 10mm initial vertical displacement, the maximum stress level reaches 0.17MPa, and for a 15mm initial vertical displacement, the maximum stress level reaches 0.25MPa.

Subsequently, the results for the strain distribution in the preloading configuration are presented in figure 10:

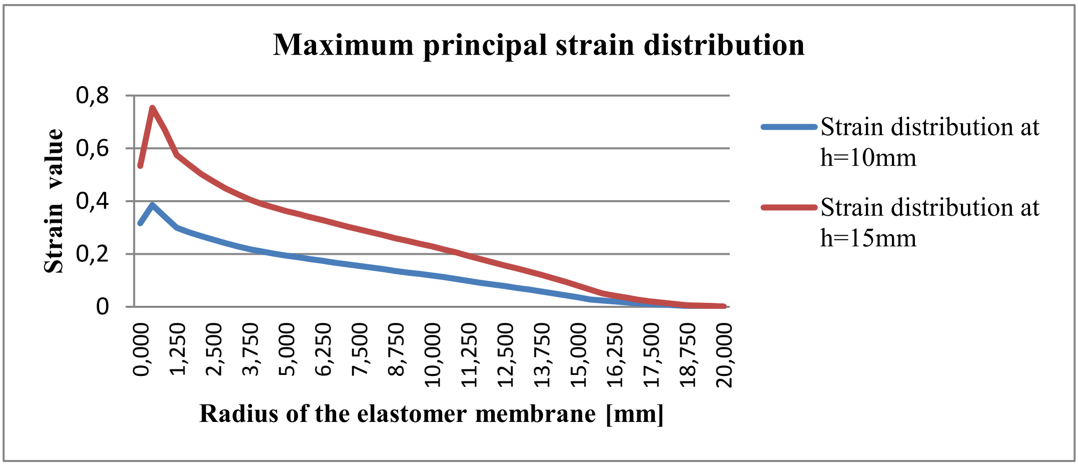

Fig. 10 – Preloading strain distribution in the elastomer membrane

The strain of the membrane is decreasing with the radius as expected, and the maximum value is predicted to be reached at a radius of 0.4 mm. The maximum strain for a 10mm initial displacement (case study 1) is 0.38, and for a 15mm initial displacement (case study 2), the highest strain level reached is 0.75.

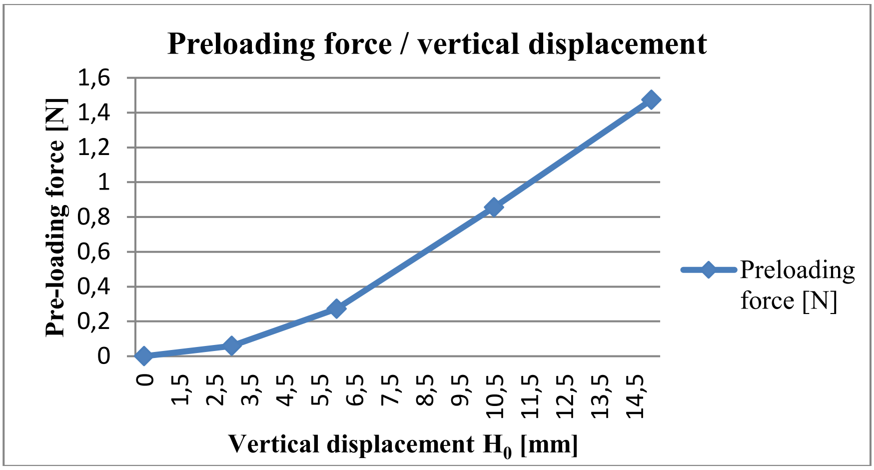

Fig. 11 – The relationship between the preloading force and the initial vertical displacement (H_0)

For the sizing design process of the preloading spring mechanism, it is crucial to study the relationship between the preloading force and the initial (preloading) vertical displacement. Using the resulted graph (Fig. 11), the stiffness of the preloading spring needs to be determined according to the desired preloading displacement.

Finally, based on the static analysis, we predicted that a 1N preloading force would be necessary to bring the membrane at a 10mm initial vertical displacement, and a 1.4N force for a 15mm initial displacement.

9. COMPLIANT ELECTRODES FOR D.E. ACTUATORS

Compliant electrodes, used to induce the electrostatic forces in the dielectric membrane, represent some of the most important aspects in the development of dielectric elastomer actuators. The electrodes need to sustain large deformations while remaining highly conductive and operate at many deformation cycles without damaging. The thickness of the electrode needs to be very small relative to the thickness of the elastomer membrane so as not to affect the stiffness of the actuator.

Carbon-graphite powder layers are considered a promising compliant electrode solution for soft actuators, due to their low stiffness and ability to remain conductive at large strain deformations [13].

There are three carbon-graphite compliant electrode concepts:

- *Carbon powder coating* - carbon particles are directly attached to the elastomer membrane using an electrostatic process. For better contact, this electrode concept can be used in combination with acrylic elastomeric elastomers, such as the VHB4910, due to the sticky nature of the elastomer.
- *Carbon grease coating* - carbon particles are bonded in a viscous material layer such as grease and applied on the elastomer.
- *Conductive elastomer* (with graphite particles) – the carbon particles are incorporated in an elastomeric thin film matrix that can be attached to the surface of the elastomers.

The advantages and disadvantages of each electrode concept are compared in the table below [13]:

Table 4. – The advantages and disadvantages for the graphite electrode concepts

	Advantages	**Disadvantages**
Carbon powder coating	• The contribution to the stiffness of the dielectric membrane can be neglected	• Difficulty at maintaining full coverage at large strains • The risk of the particles to detach from the elastomer in time. • Not suitable for long term applications
Carbon grease coating	• The contribution to the stiffness of the dielectric membrane can be neglected • Easier to handle than carbon powder and capable of sustaining larger strains while remaining highly conductive	• Long term stability issues caused by the diffusion into the elastomer of the viscous substance
Conductive elastomer	• The most suitable electrode concept for long term applications	• The contribution to the stiffness of the elastomer membrane cannot be neglected • Unsuitable for thin dielectric membranes

10. MOUNTING AND IMPLEMENTATION OF THE D.E ACTUATORS IN THE MORPHING STRUCTURE

To be able to morph the thickness distribution of the airfoil, the proposed conical actuator will be used in an actuation array mounted under the wing skin. Using a grid actuation, we can modify the shape of the airfoil with high fidelity, according to the aerodynamic parameters, in order to improve the efficiency of the wing. The objective is to promote laminar flow over a large wing surface by delaying the flow transition location towards the trailing edge. In the images below (Fig. 12) we can see the graphical representation of the proposed actuation array concept:

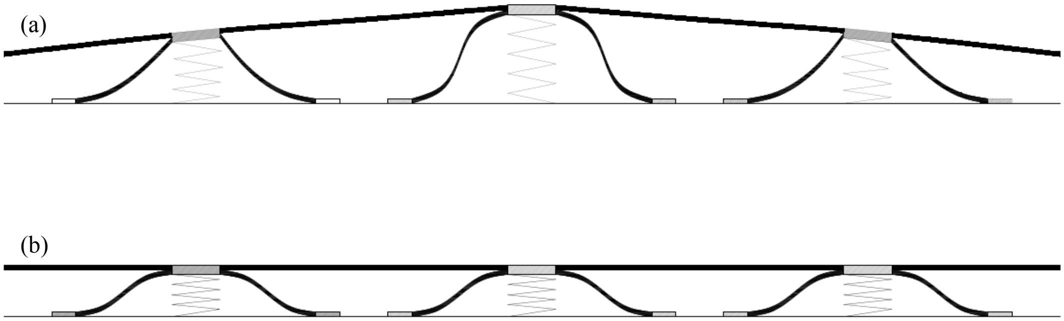

Fig. 12 – The proposed actuation array for variable-thickness morphing structures (a) actuated; (b) un-actuated

The operation of the grid can be controlled by a micro-controller that will regulate the output signal for each actuator in order to modify the airfoil geometry of the wing according to the data received by the aerodynamic receptors. For better operational performances, we can group the actuators in clusters with separate micro-controllers connected to a central processing unit (CPU). The control algorithm is presented in Fig. 13.

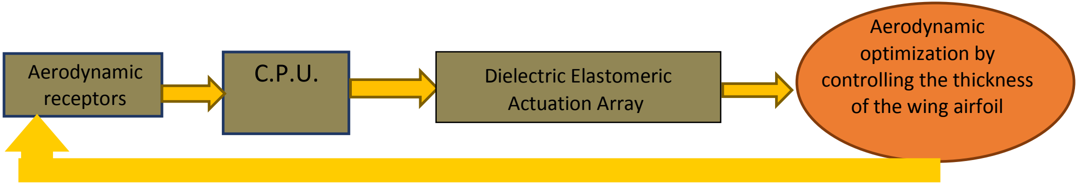

Fig. 13 – The proposed feedback morphing control algorithm

11. CONCLUSIONS AND DISCUSSIONS

One of the main goals of this paper was to address the design stages for the development of the D.E. morphing actuators (elastomer material selection, electrode selection and preloading configuration) and to contribute to the development of morphing wing dielectric elastomer actuators and also to a more efficient and sustainable future of modern aviation. In this paper, a conical preloading configuration for dielectric elastomers has been studied using the FE method. Important data were reported during this study that will be used for the further development of the proposed morphing actuators. The design challenges in developing morphing dielectric elastomer actuators have been highlighted (such as the environmental perturbations), and different graphite compliant electrode concepts have been reviewed.

Finally, an actuation array system has been proposed for the mounting of the D.E. actuators in the morphing structure.

The limitation of this research represents the lack of experimental data necessary for the further study and development of the actuators. However, in the future of this research project, experimental models and prototypes will be designed and tested using specific procedures to characterize the static and dynamic performances and validate the theoretical and computational results presented in this paper.

Further experimental studies should be performed to predict the long-term operational performances of the actuators. One of the additional required investigations would be the creep and material relaxation in the conical preloading configuration.

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