Feasibility study for an active envelope based on electroactive polymers for a blimp

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Feasibility Study for an Active Envelope Based on Electroactive Polymers for a Blimp

Diploma Thesis WS06/07

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Centre of Structure Technologies

Swiss Federal Institute of Technologies Zurich
Abstract

Since the propulsion of non-rigid airships (blimps) through classical propellers is inefficient, the required thrust could be obtained through the imitation of the fish-like motion by locally deforming the blimp body through dielectric elastomer (DE) membrane actuators. The active envelope segment is composed of a lightweight and helium-tight membrane, which is characterized by a high tensile strength and a high compressive compliance, and by a DE-actuator consisting of at least one stretched dielectric film layer coated on both sides with compliant electrodes. During the manufacturing process the over-stretched DE-actuator is attached directly to the tight blimp envelope. If the actuator exerts a resulting force larger than that induced by the internal pressure in the envelope, the membrane below the DE-actuator will wrinkle. By applying an electrical voltage to the DE-actuator, the active envelope segment regains its fully elongated state.

In this diploma thesis the feasibility of the proposed solution for an active envelope is investigated. The mechanical stress distribution in the blimp envelope due to internal pressure was calculated. Furthermore, the envelope strain and strain rate requirements for steady and unsteady locomotion were determined. The fulfillment of the mechanical stress and strain requirements was theoretically investigated through a hyperelastic model for the DE-actuator. In order to experimentally simulate the stress state of the blimp envelope, a cruciform functional model of the active envelope was defined and experimentally characterized through an in-house made testing device. The results show the fulfillment of the mechanical stress and strain requirements for steady swimming.
Zusammenfassung


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<th>Description</th>
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<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>DE</td>
<td>Dielectric Elastomer</td>
</tr>
<tr>
<td>DIC</td>
<td>Digital Image Correlation</td>
</tr>
<tr>
<td>EAP</td>
<td>Electro Active Polymer</td>
</tr>
<tr>
<td>EMPA</td>
<td>Swiss Federal Laboratories for Materials Testing and Research</td>
</tr>
<tr>
<td>ETHZ</td>
<td>Swiss Federal Institute of Technology Zurich</td>
</tr>
<tr>
<td>PAL</td>
<td>Phase Alternation Line</td>
</tr>
</tbody>
</table>
### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{Active}$</td>
<td>Active area of the DE-actuator</td>
</tr>
<tr>
<td>$A_{Blimp}$</td>
<td>Blimp surface area</td>
</tr>
<tr>
<td>$A_{Total}$</td>
<td>Total area of the DE-actuator</td>
</tr>
<tr>
<td>$A_{V,Blimp}$</td>
<td>Reference area of the blimp (reference area = $\text{volume}^{2/3}$)</td>
</tr>
<tr>
<td>$A_{V,Trout}$</td>
<td>Reference area of the trout (reference area = $\text{volume}^{2/3}$)</td>
</tr>
<tr>
<td>$C_{DV,Blimp}$</td>
<td>Drag coefficient of the blimp body (reference area = $\text{volume}^{2/3}$)</td>
</tr>
<tr>
<td>$C_{DV,Trout}$</td>
<td>Drag coefficient of the trout body (reference area = $\text{volume}^{2/3}$)</td>
</tr>
<tr>
<td>$d$</td>
<td>Airfoil thickness</td>
</tr>
<tr>
<td>$D$</td>
<td>Shortest distance from the backbone to the lateral side</td>
</tr>
<tr>
<td>$d/l$</td>
<td>Thickness to length ratio</td>
</tr>
<tr>
<td>$dA$</td>
<td>Infinitesimal surface area</td>
</tr>
<tr>
<td>$d_H$</td>
<td>Trout width</td>
</tr>
<tr>
<td>$d_S$</td>
<td>Trout height</td>
</tr>
<tr>
<td>$d\varepsilon/dt$</td>
<td>Strain rate</td>
</tr>
<tr>
<td>$d\lambda/dt$</td>
<td>Stretching rate</td>
</tr>
<tr>
<td>$f$</td>
<td>Electrical activation frequency</td>
</tr>
<tr>
<td>$F_{D,Blimp}$</td>
<td>Drag force of the blimp</td>
</tr>
<tr>
<td>$F_{D,Trout}$</td>
<td>Drag force of the trout</td>
</tr>
<tr>
<td>$F_{T,Blimp}$</td>
<td>Thrust force of the blimp</td>
</tr>
<tr>
<td>$F_{T,Trout}$</td>
<td>Thrust force of the trout</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity acceleration</td>
</tr>
<tr>
<td>$h$</td>
<td>Dielectric film thickness</td>
</tr>
<tr>
<td>$L$</td>
<td>Actual length of the stretched dielectric film</td>
</tr>
<tr>
<td>$L_0$</td>
<td>Dielectric film length by non-activated state</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Dielectric film length by partially activated state</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Dielectric film length by fully activated state</td>
</tr>
<tr>
<td>$L_{\text{ORIGIN}}$</td>
<td>Original length of the non-stretched dielectric film</td>
</tr>
<tr>
<td>$L_S$</td>
<td>Vertebral column segment length</td>
</tr>
<tr>
<td>$L_{x,\text{ELECTRODE}}$</td>
<td>Actual electrode length in x-direction (longitudinal blimp direction)</td>
</tr>
<tr>
<td>$L_{y,\text{ELECTRODE}}$</td>
<td>Actual electrode length in y-direction (transversal blimp direction)</td>
</tr>
<tr>
<td>$M$</td>
<td>Moment</td>
</tr>
<tr>
<td>$N$</td>
<td>Line load or force-per-unit length</td>
</tr>
<tr>
<td>$N_x$</td>
<td>Line load (or force per unit length) in $x$-direction of the DE-actuator</td>
</tr>
<tr>
<td>$N_y$</td>
<td>Line load (or force per unit length) in $y$-direction of the DE-actuator</td>
</tr>
<tr>
<td>$N_\theta$</td>
<td>Line load (or force per unit length) in transversal blimp direction</td>
</tr>
</tbody>
</table>

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$N_p$ [N/m] Line load (or force per unit length) in longitudinal blimp direction

$p_{electrode}$ [Pa] Electrostatic pressure

$P_{T,Blimp}$ [W] Power of the blimp

$P_{SR\_DE}^*$ [W/m²] Power per unit area of the spring roll DE actuator

$Q$ [F] Shearing force

$R$ [m] Local radius of curvature of the vertebral column

$r_0$ [m] Radius of a parallel circle

$r_1, r_2$ [m] Local radii of curvature of the blimp envelope

$R_{TOT}$ [N] Resultant of the total load on a shell portion

$t$ [$\mu$m] Blimp envelope thickness

$U$ [V] Voltage

$v_0$ [m/s] Trout cruising speed

$v_{Blimp}$ [m/s] Blimp cruising speed

$v_{Trout}$ [m/s] Trout cruising speed

$X$ [m] Major semi-axis of a symmetrical ellipsoid

$Y$ [m] Minor semi-axis of a symmetrical ellipsoid

$y(x)$ [m] Reconstructed midline function

$Y_L, Z_L$ [Pa] External load on a infinitesimal surface area

$\Delta h$ [m] Water column height

$\Delta L_S$ [m] Skin elongation

$\Delta p$ [Pa] Internal pressure

$\varepsilon$ [-] Strain related to the original (non-stretched) dielectric film length

$\varepsilon(U)$ [-] Activation strain related to the actuator length at non-activated equilibrium state between the pre-stretched and the activated dielectric film states

$\varepsilon_0$ \[ \frac{A \cdot s}{V \cdot m} \] Free space permittivity

$\varepsilon_{01}$ [-] DE-actuator strain in longitudinal direction related to the actuator length at non-activated equilibrium needed to achieve the non-bended body state

$\varepsilon_{02}, \varepsilon_{\phi}$ [-] DE actuator strain in longitudinal direction related to the actuator length at non-activated equilibrium needed to achieve the fully bended state

$\varepsilon_{10}$ [-] Strain of the concave blimp body side related to the skin length by non-bended body state

$\varepsilon_{12}$ [-] Strain of the convex blimp body side related to the skin length by non-bended body state

$\varepsilon_r$ [-] Relative permittivity of the dielectric film VHB4910 (dielectric constant)

$\varepsilon_{Skin}$ [-] Lateral skin strain in longitudinal direction

$\eta_{E-M}$ [-] Electromechanical efficiency

$\eta_{M-F}$ [-] Mechanical-Fluidodynamical efficiency

$\theta$ [-] Transversal membrane coordinate

$\kappa(x)$ [m⁻¹] Local curvature of the vertebral column

$\lambda$ [-] Stretching ratio
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda(U=0)$</td>
<td>[-]</td>
<td>Stretching ratio by non-activated equilibrium state related to the original (non-stretched) dielectric film length</td>
</tr>
<tr>
<td>$\lambda(U&gt;0)$</td>
<td>[-]</td>
<td>Stretching ratio by activated equilibrium state related to the original (non-stretched) dielectric film length</td>
</tr>
<tr>
<td>$\lambda_{OVER}$</td>
<td>[-]</td>
<td>Over-stretching ratio related to the original (non-stretched) dielectric film length</td>
</tr>
<tr>
<td>$\rho_{Air}$</td>
<td>[kg/m$^3$]</td>
<td>Air density</td>
</tr>
<tr>
<td>$\rho_{Water}$</td>
<td>[kg/m$^3$]</td>
<td>Water density</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>[-]</td>
<td>Longitudinal membrane coordinate</td>
</tr>
</tbody>
</table>
Acknowledgments

I wish to express my gratitude to everyone who contributed to this project, in particular to my advisor Silvain Michel. I would like to wish him every success for his future projects.

I also want to thank Prof. Dr. Paolo Ermanni from the Centre of Structure Technologies for allowing me to write my diploma thesis on such an interesting topic.

Many thanks go out to Urs Hintermüller for his suggestions, comments, and essential contributions to the realization of the required components.

Finally I would like to thank Patrick Lochmatter for his valuable and competent advices.
1 Introduction

1.1 Lighter-Than-Air Airships

A lighter-than-air airship or dirigible is a buoyant aircraft that can be steered and propelled through the air. Unlike aerodynamic crafts (e.g. airplanes and helicopters), which stay aloft by moving an airfoil through the air in order to produce lift, aerostatic crafts such as airships and balloons stay aloft primarily by means of a cavity (usually quite large) filled with a gas of lesser density than the surrounding atmosphere. Hydrogen and helium are the most commonly used lifting gases. Helium (18 \( g/m^3 \)) is twice as heavy as (diatomic) hydrogen (9 \( g/m^3 \)) and both gases are lighter than air. Since the hydrogen is inflammable the noble gas Helium is preferred. Both provide about 1 kilogram of lift per cubic meter of gas at room temperature and sea level.

Airships are usually divided in three main categories: a) non-rigid airships, b) semi-rigid airships and c) rigid airships.

a. Non-rigid airships or blimps use an internal pressure level in excess of the surrounding air pressure in order to retain their shape (Fig. 1-1 a). They don’t have an interior skeleton or supporting structure. The gondola and the tail units are mounted on the airship envelope. The load due to the gondola is transferred from the lower to the upper envelope area via large-surface patches. This so-called catenary curtains transfer force to the upper envelope section and ensure the even distribution of the weight in the blimp envelope [34].

b. Semi-rigid airships differ from the blimps because of the presence of an articulated keel frame running along the bottom of the envelope to distribute the suspension loads into the envelope and allow lower envelope pressures (Fig. 1-1 b). These aircrafts, analogously to blimps, get their shape from the internal lifting gas pressure.

c. Rigid airships like the Zeppelins have a rigid frame structure containing multiple, non-pressured gas cells or balloons to provide the needed lift (Fig. 1-1 c). The development of this airship type was abandoned after the most spectacular and widely remembered airship accident, i.e. the burning of the Hindenburg on 6 May 1937.
Fig. 1-1: Airship categories: (a) non-rigid airship, the “Spirit of Innovation” of the Goodyear company fleet [35]; (b) semi-rigid airship, the Zeppelin NT [36]; (c) rigid airship, U.S. Navy Zeppelin ZRS-5 "USS Macon".

Non-rigid and semi rigid airships have in their inside two or more ballonets. These airbags can be imagined as “balloons inside a balloon”. Since air density changes with altitude and temperature, the lifting gas in a completely filled envelope would expand or contract and thereby influence the pressure difference existing between the surrounding air and the inner lifting gas. In order to keep this pressure difference constant and maintain the aerodynamic shape of the blimp, the air quantities in the ballonets is varied. Ballonets are not only used to compensate the volumetric fluctuations of the lifting gas but also to trim the blimp.

Most of the recent non-rigid, helium filled airships bodies, are made from multiple layers of coated fabrics and/or laminated fabric/film materials produced in roll form. Desirable properties for use in pressurised airship envelopes are high strength, high strength to weight ratio, resistance to environmental degradation through temperature, humidity and ultraviolet light, high tearing strength and low helium permeability [1]. The most modern envelope materials are laminates. The feature of laminates is that the previously required properties can be tailored by the judicious selection of appropriate components. Thus, the laminate will consist of components for load bearing, gas retention and to protect against weathering. The single laminae are bonded together through adhesive layers (Fig. 1-2). Potential load bearing fabrics are based on Polyester (e.g. Terylene, Dacron), Polyamide (e.g. Nylon) and Aramid high-modulus (e.g. Kevlar 49). The gas retention layer can be a coating or a film. Polyester (e.g. Mylar, Hytrel) films are again the preferred materials. Effective environmental/weathering protection materials are PolyvinylFluoride (e.g. Tedlar) and Polyurethane [1, 2, 3].
In the last decades airships have found three main applications: The first one is as high altitude, long duration, sensor and/or communication platform for military purposes [37]. The second one is as long distance means of transport for very large payloads [38]. The last and most common application is for advertising purposes. Since airships can hold their position and can be viewed over a large expanse, they are excellent mediums for advertising at large outdoor events.

At present, future applications of unmanned blimps as buoyant life investigating mobile platform for in situ exploration of Mars and Titan are investigated. The blimp could carry various instrument packages including camera, visible spectrometer and gas chromatograph/mass spectrometer, which would allow the life detection on these planets [4-6]. The employment of non-rigid and semi-rigid airships as unmanned stratospheric platforms for communication purposes is actually under development [2, 7].

### 1.2 Propellers as Propulsion System for Airships

Nowadays airships are driven exclusively through propellers (see Fig. 1-3). Electrical or combustion engines provide the required power to the propellers through a rotating shaft. The typical rotational frequencies for airships propellers are in the range of 1000-3000 revolutions per minute. Generally the propeller diameter doesn’t exceed 2 meters. Propulsion systems based on propellers applied to airships are inefficient for the following reasons. Since the cross-sectional area of an airship body is larger than that of the propellers, the velocity of the air flow behind the propeller must be significant higher than the airship cruising speed. As the velocity difference between the wake behind the airship body and that induced by the propellers affects directly the efficiency [8], this drive propulsion system results ineffective applied to airships. Furthermore, since the exceeding of the Mach number would lead to significant energetic losses, the propeller rotational frequencies have to be limited. Also the size of the propellers is limited to avoid supersonic relative tip mach numbers.
Both limitations are responsible for the relative low airship cruising speed. To overcome these disadvantages the number of propellers should be increased. Unfortunately this solution would lead to an ineffective airship construction and to an important increase of the overall aircraft weight.

Fig. 1-3: Airship propellers: (a) propeller without housing; (b) propeller with vectorial steering system in operation.

1.3 Fish-like Thrust Generation as Alternative to Propeller Propulsion Systems

A possible alternative to the inefficient propulsion system based on propellers is suggested by the nature. It consists in the imitation of the fish-like motion in order to achieve the needed thrust. In nature several fish-like thrust generation types can be recognized. Colgate [9] and Sfakiotakis [10] give a good classification of fish species and the associated swimming motions. In particular Hertel [8] described and analyzed in detail the hydrodynamic of the rainbow trout. The trout produces thrust through an oscillating bending of the body and an opposite bending of the caudal fin. In Fig. 1-4 these opposite bendings can be recognized for both steady and unsteady swimming.

Fig. 1-4: Body and caudal tailfin motion of the rainbow trout [8]: (left) steady swimming; (right) unsteady swimming.

Fig. 1-5 shows a comparison of propulsive efficiency for four species of small whales and a typical marine propeller as a function of the thrust
coefficient. The superiority of the oscillatory motion is unquestionable. The efficiency of the fish-like undulatory thrust generation is significantly higher and also for a broad range almost constant. The major advantage of this locomotion concept is that thrust is generated at the same location where body induced momentum losses occur [11]. The propeller system has only at one specific thrust coefficient a maximum and decays drastically for both sides of the maximum.

Fig. 1-5: Comparison of relationships of propulsive efficiency and thrust coefficient for four species of small whales and a typical marine propeller [12].

1.3.1 Fluidodynamical Feasibility

In order to apply the locomotion mechanism of a fish in water to a deformable airship in air, the geometrical shapes of the fish and airship have to be similar. Furthermore the fluidodynamical similarity must be fulfilled. Krämer [11] indicated the rainbow trout geometry and locomotion as appropriate for a deformable airship. Since the oscillatory thrust generation system requires a deformable body, its application is restricted only to non-rigid or semi-rigid airships. The body shape of a rainbow trout is shown in Fig. 1-6.

Fig. 1-6: Resulting profile shape from the geometry of a rainbow trout [8].
The trout body is not rotationally symmetric. The height $d_S$ is significantly larger than the width $d_H$. The trout shape can be approximated by an airfoil profile (NACA 63016) [8] with maximal thickness $d$ defined as:

$$d = \frac{d_S + d_H}{2} \quad (1)$$

- $d_S$ [m] Trout height
- $d_H$ [m] Trout width
- $d$ [m] Airfoil thickness

The typical thickness-to-length ratio ($d/l$) for the resulting profile shape based on the geometry of an adult rainbow trout is equal to 0.18, whereas the maximum thickness is located at 0.4 of the body length ($x/l = 0.4$). For simplicity in this feasibility study the author adopts as resulting blimp shape a rotationally symmetric ellipsoid with the same thickness-to-length ratio $d/l = 0.18$ defined by Hertel [8] and maximal thickness located at $x/l = 0.5$ of the body length.

In order to transpose the motion of the trout to the deformable blimp, the fluid dynamical similarity has to be applied. The relevant non-dimensional parameters are:

a. Reynolds number
b. Strouhal number
c. Mach number
d. Froude number

The cruising speed of the blimp will be relatively small, in the order of 1-10 [m/s]. Thus, the Mach number will be very small. Since the compressibility becomes relevant at 1500 [m/s] in water and 330 [m/s] in air, the Mach number is not considered. The Froude Number correlates the inertial forces with the gravitational ones. In literature related to fish-like locomotion the Froude number is sometimes considered as the propulsive efficiency. Furthermore the Froude number of the blimp in air doesn’t have to be concordant with that of a fish in water [11]. Moreover the gravitational forces are not relevant. Therefore the conditions needed to transpose the locomotion of a trout in water to a blimp in air are dictated exclusively by the Reynolds and Strouhal numbers. The first one describes the friction forces, while the second one the oscillating flow mechanisms. A steadily swimming 0.3 meters long trout ($d/l = 0.18$, $x/l = 0.4$) with a body-caudal-fin-beat frequency of 4.5 [Hz] reaches a velocity of 1.2 [m/s] [8]. The amplitude of the tail movement reaches 20 [%] of the total fish length. The corresponding Reynolds and Strouhal numbers amount to:

$$Re = \frac{\nu_0 \cdot L \cdot \rho}{\mu} = \frac{1.2 \frac{m}{s} \cdot 0.3m \cdot 1000 \frac{kg}{m^3}}{1.002 \cdot 10^{-3} \frac{kg}{m \cdot s}} = 0.36 \cdot 10^6 \quad (2)$$

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In order to fulfill the fluidodynamical similarity a 6 meters long blimp has to perform the oscillatory motion with a body-caudal-fin-beat frequency of 0.2 [Hz] (the tail amplitude is equal to $20\% \cdot 6 \, [m] = 1.2 \, [m]$). According to the Reynolds number the blimp achieves a cruising speed of 1.03 [m/s]. Thus, from a fluidodynamical point of view the fish-like oscillatory motion can be transposed to a blimp.

### 1.4 Fish-like Locomotion of a Blimp Through Active Membranes

As discussed in section 1.3, the fish-like propulsion system represents thanks to its high efficiency a valid alternative to classical propellers for airships. The achievement of this locomotion can be obtained through different mature and reliable technologies like pneumatic or electrical actuators. Unfortunately the weight of such actuators limits strongly their application for this purpose. A possible solution is given by active membranes. Active membranes are mechanisms which possess the capability to change their shape in a controlled way. Fig. 1-7 shows schematically how through an aimed deformation of the blimp envelope by means of active membranes the double bending of the rainbow trout body can be imitated.

![Fig. 1-7: A blimp body deformed through active membranes (in red).](image)

The active membrane considered in this work is based on Dielectric Elastomer (DE) actuators, which are a sub-class of the Electroactive Polymers (EAP). In sections 1.5 and 1.6 both concepts are presented and explained.

### 1.5 Electroactive Polymers (EAP)

Electroactive polymers (EAP) are an emerging class of actuation materials. Their large electrically induced strains (longitudinal or bending), low density, mechanical flexibility, and ease of processing offer advantages over
traditional electroactive materials. Two general classes of EAP can be identified. The first class is ionic EAP, which requires relatively low voltages (< 10 \([V]\)) to achieve large bending deflections. This class usually needs to be hydrated and electrochemical reactions may occur. The second class is Electronic-EAP and it involves piezoelectric, electrostrictive and/or Maxwell stresses. These materials can require large electric fields (> 100 \([MV/m]\)) to achieve longitudinal deformations in the range of 4 – 380 [%] \([13]\). In Tab. 1-1 the leading EAP materials are listed according to their class.

<table>
<thead>
<tr>
<th>Ionic EAP</th>
<th>Electronic EAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Nanotubes (CNT)</td>
<td>Dielectric EAP (DE)</td>
</tr>
<tr>
<td>Conductive Polymers (CP)</td>
<td>Electrostrictive Graft Elastomers</td>
</tr>
<tr>
<td>ElectroRheological Fluids (ERF)</td>
<td>Electrostrictive Paper</td>
</tr>
<tr>
<td>Ionic Polymer Gels (IPg)</td>
<td>Electro-Viscoelastic Elastomers</td>
</tr>
<tr>
<td>Ionic Polymer Metallic Composite (IPMC)</td>
<td>Ferroelectric Polymers</td>
</tr>
</tbody>
</table>

Tab. 1-1: List of the leading EAP materials \([14]\).

### 1.5.1 Ionic EAP Materials

These materials usually contain an electrolyte and they involve transport of ions/molecules in response to an external electric field. Examples of such materials include conductive polymers/polyaniline actuators, IPMC, and ionic gels. The field controlled migration or diffusion of the various ions/molecules results is an internal stress distribution. These internal stress distributions can induce a wide variety of strains from volume expansion or contraction to bending. In some conductive polymers the materials exhibit both ionic and electronic conductivities. These materials are relatively new as actuator materials and have received much less attention in the literature than the piezoelectric and electrostrictive materials \([13]\).

### 1.5.2 Electronic EAP Materials:

These are mostly materials that are dry and are driven by the electric field or Coulomb forces. This category includes piezoelectric, electrostrictive and ferroelectric materials. Generally these materials are polarizable with the strain being coupled to the electric displacement. The strain of electrostrictor and ferroelectric materials is proportional to the square of the polarization or electric displacement. In piezoelectric materials the strain couples linearly to the applied field or electric displacement. Charge transfer in these materials is in general electronic and at DC field these materials behave as insulators. Another group of EAP materials that belongs to this class are dielectric polymers, which are mechanically very soft and easily compressed by the Coulomb forces associated with electrode charge. The strain in these materials is nominally proportional to the square of the polarization \([13]\).
1.6 Dielectric Elastomers (DE)

Among the electroactive Polymers (EAP) the Dielectric Elastomers (DE) constitute very promising preliminary results for various future applications where large deformations and low forces are needed [15]. Tab. 1-2 shows a comparison of selected actuator technologies in terms of characteristic actuator parameters.

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>Maximum Strain [%]</th>
<th>Maximum Pressure [MPa]</th>
<th>Specific Elastic Energy Density [J/g]</th>
<th>Elastic Energy Density [J/cm²]</th>
<th>Maximum Efficiency [%]</th>
<th>Relative Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Elastomers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acrylic</td>
<td>380</td>
<td>8.2</td>
<td>3.4</td>
<td>3.4</td>
<td>60-80</td>
<td>Medium</td>
</tr>
<tr>
<td>Silicone</td>
<td>63</td>
<td>3.0</td>
<td>0.75</td>
<td>0.75</td>
<td>90</td>
<td>Fast</td>
</tr>
<tr>
<td>Piezoelectric Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic (PZT)</td>
<td>0.2</td>
<td>110</td>
<td>0.013</td>
<td>0.10</td>
<td>&gt;90</td>
<td>Fast</td>
</tr>
<tr>
<td>Single Crystal (PZN-PT)</td>
<td>1.7</td>
<td>131</td>
<td>0.13</td>
<td>1.0</td>
<td>&gt;90</td>
<td>Fast</td>
</tr>
<tr>
<td>Shape Memory Alloy (TiNi)</td>
<td>&gt;5</td>
<td>&gt;200</td>
<td>&gt;15</td>
<td>&gt;100</td>
<td>&lt;10</td>
<td>Slow</td>
</tr>
</tbody>
</table>

Tab. 1-2: Comparison of selected actuator technologies [16].

Compared to Piezoelectric Materials and Shape Memory Alloys Dielectric Elastomers show good overall performances. For these reasons DE have emerged as promising multifunctional smart energy-transduction materials in several actuation, sensing, and electric power generation applications [17].

1.6.1 Structure and Working Principle of the Dielectric Elastomer Actuators

Dielectric elastomer actuators are constituted by a dielectric elastomeric film, which is coated on both sides with a compliant electrode (Fig. 1-8 a). The electrodes can be connected through an external electrical circuit to a high voltage source (Fig. 1-8 b). By applying an electric voltage (~ kV) to the electrodes, electrical charges move from one electrode to the other [18]. The resulting electrostatic pressure between the charged electrodes squeezes the dielectric film in thickness direction. As the dielectric elastomeric film is incompressible, the compression in thickness direction must be compensated by a planar expansion (Fig. 1-8 c). This working principle can be used for the manufacturing of various types of actuators. In this diploma thesis the focus is on the application of DE as active actuator for an active envelope for a blimp.
Fig. 1-8: (a) Structure of a dielectric elastomer (DE) actuator; (b) DE actuator with electrical circuit in short circuited state (non-activated state); (c) DE actuator under activation (activated state).

The dielectric elastomer actuators manufactured at EMPA Dubendorf [39] consist of the acrylic film VHB4910 of the company 3M [40], which is stretched in planar direction through a stretching machine. Since the dielectric material is incompressible this biaxial stretching leads to a reduction of the film thickness. The stretching procedure is justified by the equation (4) [19], which gives the electrostatic pressure $p_{\text{electrostatic}}$ of the compliant electrodes under electrical activation as a function of the applied electrical voltage $U$, the dielectric film thickness $h$, the free space permittivity $\varepsilon_0$, and the relative permittivity of the dielectric film VHB4910 $\varepsilon_r$.

$$p_{\text{electrode}} = \varepsilon_0 \cdot \varepsilon_r \cdot \left( \frac{U}{h} \right)^2 = \varepsilon_0 \cdot \varepsilon_r \cdot E^2 \quad (4)$$

- $p_{\text{electrode}}$ [Pa] Electrostatic pressure
- $U$ [V] Voltage
- $h$ [m] Dielectric film thickness
- $\varepsilon_0$ [A·s/V·m] Free space permittivity
- $\varepsilon_r$ [-] Relative permittivity of the dielectric film VHB4910

The pressure exerted by the electrodes on the DE is proportional to the square of the electric field. Under activation with constant voltage the pressure depends with $1/h^2$ on the film thickness. In other words: the thinner the film is, the more planar elongation is achieved.

1.6.2 Applications of Dielectric Elastomer Actuators

Because of their unique characteristics and expected low cost, dielectric elastomer actuators are under development in a wide range of applications including multifunctional (combined actuation, structure, and sensing).
muscle-like actuators for biomimetic robots; microelectromechanical systems (MEMS); smart skins; conformal loudspeakers; haptic displays; and replacements for electromagnetic and pneumatic actuators for industrial and commercial applications [20]. Dielectric elastomers have shown unique performance in each of these applications; however, some further development is required before they can be integrated into products and smart-material systems. Among the many issues that may ultimately determine the success or failure of the technology for specific applications are durability, operating voltage, power requirements, the size, cost, and the complexity of the required electronic driving circuitry [20].

1.7 Structure of the Active Envelope Based on DE Actuators

As anticipated in section 1.4 the active membrane considered in this diploma thesis is based on dielectric elastomers (DE). The fish-like motion can be achieved through an aimed deformation of the blimp body through biaxially stretched DE actuators attached directly on the envelope. Thus, the active deformable blimp envelope consists of two main components:

a. Blimp envelope
b. DE-actuator

The blimp envelope is a flexible, lightweight and helium-tight membrane, which is characterized by a high tensile strength and a high compressive compliance (the wrinkling of the membrane is desired). Aluminized balloon envelopes satisfy these mechanical requirements. Thanks to their small thicknesses (< 50 [µm]), they can be wrinkled easily. Besides the metal coating grantees the required gas tightness. Since the stresses induced by the helium internal pressure are relatively low, classical laminates fabrics for airships are not taken in account. The envelope can be cut in segments that are successively welded together in order to achieve a gas-tight body with high compliance under compression forces.

The dielectric elastomer actuator consists of at least one stretched dielectric layer coated on both sides with conductive and compliant electrodes connected to an external high voltage source (see section 1.6.1). The stretched DE actuator is applied to the tight blimp envelope, which is subjected to biaxial line loads induced by the internal pressure (Fig. 1-9 a). If the forces exerted by the stretched DE are larger than that due to the internal pressure, the blimp envelope segment wrinkles till a non-activated equilibrium of forces is achieved (Fig. 1-9.b). The wrinkled envelope can regain its fully-elongated state through the electrical activation of the DE-actuator (activated equilibrium of forces) (Fig. 1-9 c). As the dielectric film is incompressible the electrical deactivation causes a contraction of the blimp envelope (Fig. 1-9.b).

This working principle allows to bend the blimp body through the aimed activation and deactivation of the DE actuators. An activation of all
actuators would lead to the original non-bended blimp shape. If the forces needed to bend the blimps body cannot be obtained through a single actuator layer, a scaling of the forces exerted by the actuators can easily be achieved by stacking several DE layers. Thus, the required fish-like motion can be realized through the local deformation of the envelope by means of EAP actuators.

Fig. 1-9: Manufacturing and structure of an active envelope segment (section view): (a) mounting of the planar over-stretched dielectric elastomer to a tight blimp envelope segment under internal pressure; (b) wrinkled blimp envelope segment (non-activated equilibrium of forces); (c) tight blimp envelope segment with activated DE-actuator (activated equilibrium of forces).

1.8 Project Tasks

In order to evaluate the feasibility of the solution proposed in section 1.7, the following tasks have to be performed. The requirements for the mechanical membrane stresses in the blimp envelope and the needed local deformations of the blimp have to be determined. A functional model of the active envelope segment must be evaluated, developed and realized. A testing device for the experimental characterization of the chosen functional model must be designed and realized. After a parameter study the test execution must be planned. From the discussion of the results of the quantitative experimental functional model characterization the feasibility of the proposed solution has to be evaluated.

1.9 Project Plan

Fig. 1-10 shows the time schedule of this work.
The first five weeks are spent for the theoretical part of this work, during which the necessary know-how is collected, the requirements for an active envelope for a blimp are determined and the functional model for the active envelope is designed. Starting from the third week the testing device for the experimental characterization of the active envelope functional models is designed, realized and validated. After the sixth week the functional models are manufactured and experimentally characterized. The experimental characterization and the evaluation of the results are performed at the same time. An intermediate and a final presentation are important part of this diploma thesis. Finally the conclusions are drawn and the feasibility of the proposed solution evaluated.
2 Determination of the Requirements for an Active Envelope

In this chapter the requirements for the active envelope are determined. Special attention is paid to the mechanical loads, the strains and the strain rate requirements. In section 2.4 all requirements are summarized.

2.1 Stress Analysis of the Blimp Envelope Loaded with Internal Pressure

Since the DE actuator is attached on the blimp envelope, it is subjected to the mechanical stresses induced by the internal pressure. Thus, the determination of the mechanical stress distribution in the blimp envelope is of capital importance.

2.1.1 Pressurization

In literature typical values for the internal pressure in the blimp body are 2-4 [hPa] [21]. The term internal pressure indicates the pressure difference between the blimp lifting gas compartment and the surrounding atmosphere. These values were also experimentally confirmed through measurements carried out on the 3 meter long penguin-shaped blimp of EMPA [39]. The internal pressure was determined through a pressure gauge constituted by a U-shaped pipe filled with water and with a tube connected to the blimp body. The height of the water column and equation (5) allows the estimation of the internal pressure.

\[ \Delta p = \rho \cdot g \cdot \Delta h \]  

\begin{align*}  
\Delta p & \quad \text{[Pa]} \quad \text{Internal pressure} \\
\rho & \quad \frac{\text{kg}}{\text{m}^3} \quad \text{Water density} \ (\rho = 998.2 \ \frac{\text{kg}}{\text{m}^3}) \\
g & \quad \frac{\text{m}}{\text{s}^2} \quad \text{Gravity acceleration} \\
\Delta h & \quad [m] \quad \text{Water column height difference} 
\end{align*}

The experimentally determined internal pressure values are listed in Tab. 2-1. In order to keep the shape of the blimp, the internal pressure has to be between 1.5 and 3 [hPa]. The maximal measured value of about 6 [hPa]
should not be exceeded, since the blimp could reach its ultimate load bearing capacity.

<table>
<thead>
<tr>
<th>Water Column Height [mm]</th>
<th>$\Delta p$ [Pa]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>107.7</td>
<td>lightly inflated</td>
</tr>
<tr>
<td>15</td>
<td>146.9</td>
<td>inflated</td>
</tr>
<tr>
<td>30</td>
<td>293.8</td>
<td>inflated</td>
</tr>
<tr>
<td>65</td>
<td>636.5</td>
<td>heavily inflated</td>
</tr>
</tbody>
</table>

Tab. 2-1: Experimentally determined internal pressure values.

For the following calculation of the stress distribution in the blimp envelope, the author assumes a reference internal pressure of 3 $[hPa]$.

2.1.2 Stress Distribution in the Blimp Envelope

The following calculations were extracted from the book of S. Timoshenko: “Theory of plates and shells” [22]. As anticipated in section 1.3.1 the rainbow trout-body is approximated with a rotationally symmetric ellipsoid with a thickness-to-length ratio of 0.18 ($d/l$) and maximal thickness located at 0.5 of the body length ($x/l$). The considered ellipsoid is a surface of revolution loaded with uniformly distributed internal pressure. Under this action the middle surface (the surface that bisects the thickness of the shell) of the ellipsoidal shell undergoes a uniform strain, and since the thickness of the shell is very small (compared to the planar dimensions), the tensile stresses can be assumed as uniformly distributed across the thickness. Since the conditions of the ellipsoidal shell are such that the bending stiffness of the blimp envelope can be neglected (very thin membrane), the problem of stress analysis is simplified, since the resultant moments $M_x$, $M_y$, $M_{xy}$ and $M_{yx}$ and the resultant shearing forces $Q_x$ and $Q_y$ (see Fig. 2-1 a) vanish. Thus, the only unknown are the three forces per unit length $N_x$, $N_y$, and $N_{xy} = N_{yx}$, which can be determined from the condition of equilibrium on the element of Fig. 2-1 b. The problem is statically determined if all external forces (in this case the blimp internal pressure) acting on the shell are known. The forces $N_x$, $N_y$ and $N_{xy} = N_{yx}$ obtained in this manner are called membrane forces and the theory of shells obtained by neglecting the bending stresses is called membrane theory.

A surface of revolution is obtained by rotation of a plane curve, in this case an ellipse, about an axis lying in the plane of the curve (broken line in Fig. 2-1 b and c). This curve is called the meridian and its plane is a meridian plane. An element of a shell is cut out by two adjacent meridians and two parallel circles, as shown in Fig. 2-1 b.
The position of the meridian is defined by an angle $\theta$, measured from some datum meridian plane. The position of a parallel circle is defined by the angle $\phi$, made by the normal to the surface and the axis of rotation. The meridian plane and the plane perpendicular to the meridian are the planes of principal curvature at a point of a surface of revolution, and the corresponding radii of curvature are denoted by $r_1$ and $r_2$ respectively. The radius of the parallel circle is denoted by $r_0$ so that the length of the sides of the element meeting at O are $r_1 \cdot d\phi$ and $r_0 \cdot d\theta = r_2 \cdot \sin(\phi) \cdot d\theta$. As a result the surface area of the element is $dA = r_1 \cdot r_2 \cdot \sin(\phi) \cdot d\phi \cdot d\theta$. As the symmetry of loading and deformation is assumed it can be concluded that there will be no shearing forces acting on the sides of the element ($N_{xy} = N_{yx} = N_{\phi\theta} = N_{\theta\phi} = 0$).

The magnitudes of the normal forces per unit length acting on the sides of the element are denoted by $N_{\theta}$ and $N_{\phi}$ as shown in Fig. 2-1 b. The intensity of the external load; which acts in the meridian plane, in the case of symmetry, is resolved in two components $Y_L$ and $Z_L$ parallel to the coordinate axes. By multiplying the forces with the differential area $dA$ we obtain the component of the external load acting on the element. The force acting in the direction of the tangent to the meridian on the upper side of the element is:

$$N_{\theta} \cdot r_0 \cdot d\theta = N_{\phi} \cdot r_2 \cdot \sin(\phi) \cdot d\theta \quad (6)$$

The force acting on the lower side in direction of the tangent to the meridian is:
\[
\left( N_\varphi + \frac{dN_\varphi}{d\varphi} \cdot d\varphi \right) \cdot \left( r_0 + \frac{dr_0}{d\varphi} \cdot d\varphi \right) \cdot d\theta
\]  

From expressions (6) and (7) by neglecting the quantities of second order, the resultant in the \(y\)-direction can be found and it is equal to:

\[
\left( N_\varphi \cdot \frac{dr_0}{d\varphi} \cdot d\varphi \cdot d\theta + \frac{dN_\varphi}{d\varphi} \cdot r_0 \cdot d\varphi \cdot d\theta \right) = \frac{d}{d\varphi} \left( N_\varphi \cdot r_0 \right) \cdot d\varphi \cdot d\theta
\]  

The component of external force in the same direction is

\[
Y_L \cdot r_1 \cdot r_0 \cdot d\varphi \cdot d\theta.
\]  

The force acting on the lateral sides of the element are equal to \( N_\theta \cdot r_1 \cdot d\varphi \) and have a resultant in the direction of the radius of the parallel circle equal to \( N_\theta \cdot r_1 \cdot d\varphi \cdot d\theta \). The component of this force in the \(y\)-direction (see Fig. 2-1 e) is

\[
- N_\theta \cdot r_1 \cdot \cos(\varphi) \cdot d\varphi \cdot d\theta
\]  

The sum of the forces of equations (8), (9) and (10) gives the equation of equilibrium in the direction of the tangent to the meridian

\[
\frac{d}{d\varphi} \left( N_\varphi \cdot r_0 \right) - N_\theta \cdot r_1 \cdot \cos(\varphi) + Y_L \cdot r_1 \cdot r_0 = 0.
\]  

The second equation of equilibrium is obtained by summing up the projections of the forces in the \(z\)-direction. The forces acting on the lower and upper sides of the element have a resultant in the \(z\)-direction equal to

\[
N_\theta \cdot r_0 \cdot d\theta \cdot d\varphi.
\]  

The forces acting on the lateral sides of the element and having the resultant \( N_\theta \cdot r_1 \cdot d\varphi \cdot d\theta \) in the radial direction of the parallel circle give a component in the \(z\)-direction of the magnitude

\[
N_\theta \cdot r_1 \cdot \sin(\varphi) \cdot d\varphi \cdot d\theta.
\]  

The external load acting on the element has in the same direction a component

\[
Z_L \cdot r_1 \cdot r_0 \cdot d\theta \cdot d\varphi.
\]
Summing up the forces (12), (13) and (14) we obtain the second equation of equilibrium

\[ N_\phi \cdot r_0 + N_\theta \cdot r_1 \cdot \sin(\phi) + Z_L \cdot r_1 \cdot r_0 = 0. \]  

(15)

From the equation (11) and (15) the forces \( N_\theta \) and \( N_\phi \) can be calculated in each particular case if the radii \( r_0 \) and \( r_1 \) and the component \( Y_L \) and \( Z_L \) of the intensity of the external load are given. Instead of the equilibrium of an element, the equilibrium of the portion of the shell above the parallel circle defined by the angle \( \phi \) can be considered (Fig. 2-2).

![Force equilibrium on a portion of the shell](image)

The equation of equilibrium is

\[ 2\pi \cdot r_0 \cdot N_\phi \cdot \sin(\phi) + R_{TOT} = 0 \]  

(16)

where \( R_{TOT} \) is the resultant of the total load on that portion of the shell. This equation can be used instead of the differential equation (11), from which it can be obtained by integration. If equation (15) is divided by \( r_0 \cdot r_1 \) it can be written in the form

\[ \frac{N_\phi}{r_1} + \frac{N_\theta}{r_2} = -Z_L \]  

(17)

where \( Z_L \) is the internal pressure. When \( N_\phi \) is obtained from (16), the force \( N_\theta \) can be calculated from (17).

The principal radii of curvature expressed by using the orthogonal coordinates \( X \) and \( Y \) in the case of an ellipse with semi-axis \( a \) and \( b \) (see Fig. 2-3) are given by the following formulas:
\[
\rho = r_2 \cdot \frac{b^2}{a^2} \quad \text{(18)}
\]

\[
\rho = \left( \frac{a^4 \cdot Y^2 + b^4 \cdot X^2}{b^2} \right)^{1/2} \quad \text{(19)}
\]

Thanks to the radii of curvature (18, 19) and equations (16) and (17) the forces per unit length \( N_\rho \) and \( N_\theta \) can be found. Then for a parallel circle of a radius \( r_0 \) we have \( R_{\text{TOT}} = -\pi \cdot \Delta p \cdot r_0^2 \) and equation (16) gives

\[
N_\rho = \frac{\Delta p \cdot r_0}{2 \cdot \sin(\phi)} = \frac{\Delta p \cdot r_i}{2} \quad \text{(20)}
\]

Substituting in Eq. (17), we get

\[
N_\theta = r_2 \cdot \Delta p - \frac{r_2}{r_i} \cdot N_\rho = \Delta p \left( r_2 - \frac{r_2^2}{2 \cdot r_i} \right) \quad \text{(21)}
\]

Fig. 2-3: Ellipsoid of revolution [22].

For the considered ellipsoidal body the semi axis \( b \) is larger than \( a \) (\( b = 3 \) [m], \( a = 0.18 \cdot 3 = 0.54 \) [m]). In Fig. 2-4 the line loads and line load ratio distribution in a quarter of a meridian plane of the blimp envelope is shown. In order to uniform the coordinates system used in Timoshenko’s theory to that in use for airships, the \( X \)-coordinate corresponds now to the axis of symmetry. The maximal line load values are reached at the centre of the ellipsoid (\( X = 0 \) [m], \( \Delta p = 300 \) [Pa]: \( N_\rho = 80 \) [N/m], \( N_\theta = 160 \) [N/m]). The ratio \( N_\theta / N_\rho \) is practically constant for the first 2/3 of the considered
meridian plane geometry and amounts to about 2. In the last third the line load ratio decreases rapidly till reaching a value equal to 1, which coincides with that of a sphere. The force per unit length by $X = 3\ [m]$ amounts to about $15\ [N/m]$.

![Line Loads Distribution in a Meridian Plane of the Blimp Envelope](image)

Fig. 2-4: Line loads and line load ratio distribution in a quarter of meridian plane of the blimp envelope.

If a DE actuator achieves a non-activated or activated equilibrium by wrinkling the blimp envelope, it will support the entire local load (for further explanations see the quasi-static model of the active envelope presented in section 3.1.2). On the other hand if the active envelope segment is tight the mechanical load induced by the internal pressure will be supported only by the blimp envelope. In order to predict if a stretched DE is able to wrinkle the envelope, on which it will be attached, the resulting forces per unit length exerted by the DE and the local line loads of the envelope have to be compared. Line load (or force per unit length), defined as the integral of the mechanical stress $[Pa]$ over the shell thickness, presents the main advantage of being independent of the thickness. In fact not only the blimp envelope and the DE present different thicknesses but also the actuator thickness changes as a function of the planar elongations of the dielectric material.

As the mechanical loads in the blimp envelope is a function of the local radii of curvature, the DE attached on it is not subjected to constant loads. For simplicity one assumes that a DE, which exerts line loads larger than that at the centre of its area due to the internal pressure, is considered able to wrinkle the envelope. This simplification leads to maximal errors of about 6 [%] at $X = 0\ [m]$ for a squared DE with side length equal to 20 [cm] (see Documentation CD: “Stress Analysis of the Blimp Envelope.xls”).
To summarize the DE actuator must be able to exert line loads equal or larger than $N_\phi(\Delta p = 300 \, [Pa]) = 80 \, [N/m]$. Since the deformation of the blimp body in $\theta$-direction is not of interest, the stretched DE can exert transversal line loads smaller than $N_\theta(\Delta p = 300 \, [Pa]) = 160 \, [N/m]$. 

### 2.2 Estimation of the Required Strains

The undulating motion of the trout can be achieved through an aimed deformation of the blimp body through biaxially stretched DE actuators attached directly on the envelope. In order to imitate this motion, the lateral skin strains of the trout in longitudinal direction have to be determined. Recent investigations on the rainbow trout regarding the muscle dynamics of steady and unsteady swimming have provided evidence that the lateral muscle shortening is in phase with changes in local midline curvature (curvature of the spinal backbone) [23]. This is not the case for fishes like the tuna [24], where the shortening to the lateral muscle is uncoupled with changes of the local midline curvature. In other words the midline kinematics of a trout allows to determine the local skin strain [24].

Undulation of the axial structures is the most general form of aquatic vertebrate locomotion. Key features of undulatory swimming are the following [25]:

a. The length of the body that is undulated
b. The frequency of undulation
c. The amplitude of lateral displacement
d. The length of the propulsive wave velocity (the velocity at which strain and curvature waves propagate along the body)

In this diploma thesis only the needed lateral strains are considered. In fact they allow to determine the functional basis of the undulatory swimming [25]. Since the local vertebral column curvature is proportional to the lateral strain, the reconstruction of the midline is of capital importance.

Bruce C. Jayne and George V. Lauder [25] propose a method for reconstructing the midline of largemouth bass (see Fig. 2-5), from picture taken from the dorsal side of a swimming fish (largemouth bass and trout have very similar shape). The principle steps are summarized in the following list:

a. The fish outlines are digitized through a frame-by-frame analysis of the dorsal image of the swimming fish.
b. Cubic spline functions are fitted to both the right and the left sides of the fish.
c. Using the outline cubic spline functions, 30 midline points are determined by an iterative computer algorithm. The coordinates of these 30 points are equidistant from the nearest left and right side outline points.
d. Cubic spline functions are fitted to the 30 midline points.

Fig. 2-5: Midline reconstruction steps for a rainbow trout (steady swimming) [25].

The equation for the polynomial are weighted such that the polynomials form a continuous curve. From the reconstructed spline function it is possible to calculate the local curvature of the vertebral column thanks to equation (22):

\[
\kappa(x) = \frac{y''(x)}{\left(1 + (y'(x))^2\right)^{3/2}}
\]

(22)

\(\kappa(x)\) \quad \text{Local curvature}

\(y(x)\) \quad \text{Reconstructed midline function}

Compared with the sides of an undulating fish, which continually change length, the bones of the axial skeleton have a relatively constant length. Thus, the trout body can be modelled like a homogeneous bending beam. For steady swimming and fast-starts (unsteady swimming) in most fishes, Shadwick et al. [23] consider the simple beam theory as accurate predictor of the in vivo measured lateral strains. Thus, by knowing the local curvature of the reconstructed vertebral column, it is possible to determine the local lateral strain related to the non-deformed skin length (see Fig. 2-6 a and b). By non-deformed state a skin segment and the corresponding vertebral column segment have equal length \(L_S\) (Fig. 2-6 a). Since the vertebral column length is constant both in non-bended and bended body state, the following expression is valid: \(L_S = R \cdot \Delta \phi\) (Fig. 2-6 b). Equations (23) and (24) provide the local lateral skin strains for the convex and concave body sides respectively:

\[
\varepsilon_{\text{Skin,Convex}} = \frac{\Delta L_S}{L_S} = \frac{(R + D) \cdot \Delta \phi - R \cdot \Delta \phi}{R \cdot \Delta \phi} = \frac{D}{R} = \kappa \cdot D
\]

(23)

\[
\varepsilon_{\text{Skin,Concave}} = \frac{\Delta L_S}{L_S} = \frac{(R - D) \cdot \Delta \phi - R \cdot \Delta \phi}{R \cdot \Delta \phi} = \frac{D}{R} = -\kappa \cdot D
\]

(24)
Skin ε [-] Lateral skin strain in longitudinal direction

ΔLS [m] Skin elongation

LS [m] Vertebral column segment length

R [m] Local radius of curvature of the vertebral column

κ [m⁻¹] Local curvature of the vertebral column

D [m] Shortest distance from the backbone to the lateral side (see Fig. 2-6 b)

Fig. 2-6: Dorsal view of the trout body modeled with the homogeneous beam theory; (a) non-bended state: the vertebral column segment and the skin segment have equal length LS; (b) bended state (R is the local radius of curvature of the vertebral column).

For this diploma thesis the author reconstructed the midline position from two characteristic pictures [8] for steady (Fig. 2-7 a) and unsteady (Fig. 2-7 b) swimming (see Documentation CD: “Midline Reconstruction Steady.xls” and “Midline Reconstruction Unsteady.xls”). The reconstructed midline was successively approximated through a polynomial function of sixth order. From the cubic polynomial functions for the left and right trout outline and the one for the midline was possible to determine the local shortest distance between backbone and lateral sides (D).
The resulting lateral strains for convex and concave side of a steadily swimming trout based on Fig. 2-7 are shown in Fig. 2-8. The backbone coordinate $\bar{x} = x/l$ is normalized over the trout length (distance between caudal tail joint and head) and has its origin in the first red dot starting from the tail and its ending in the last red dot shown in Fig. 2-7. The maximal strain is 7 [$\%$] and it is located at $x/l = 0.18$ of the body length. This value is consistent with that measured by Bruce C. Jayne and George V. Lauder [25] of 6.6 [$\%$]. Noteworthy is the light strain inversion between $x/l = 0.45$ and 0.76, which achieve a maximum of about 1.9 [$\%$] at $\bar{x} = 0.57$. 

Fig. 2-8: Lateral strains for steady swimming.
The lateral strain distribution on the convex and concave side of the unsteadily swimming trout of Fig. 2-7 is summarized in Fig. 2-9. The maximal strains are achieved at $\bar{x} = 0.35$ and 0.61 and are 35.5 [%] and 35.4 [%] respectively. Also for the unsteady swimming a light strain inversion can be observed ($\bar{x} = 0.86, \varepsilon = 6.8 [%]$). The last maximum is in correspondence with the head joint and amount to about 28 [%] at $\bar{x} = 0.96$.

J. A. Goldbogen and al. measured a maximal strain of 31 [%] at about the same location (second maximum). The difference between the estimated and experimentally determined maximal strain could be due to the inaccuracy by the midline approximation through a single polynomial function (Bruce C. Jayne and George V. Lauder suggest a discretization of the midline function through several cubic polynomial function).

Fast-starts are transient, high acceleration maneuvers initiated at rest or imposed upon a period of steady swimming. This mode of locomotor behaviour is critical for predatory avoidance or prey capture in a variety of fishes.

The unsteady locomotion for the blimp holds a less important role than by fishes. Thus, the quite large strain requirement can be considered as tolerant (the requirement fulfillment is not mandatory). In fact, the desired cruising speed of about 1 [m/s] could be achieved with a slower acceleration through the steady swimming. On the other hand the strain requirement of 7 [%] for the steady locomotion has to be considered fix. In fact its fulfillment is a necessary condition to reach and maintain the required cruising speed.

An interesting and positive aspect that characterize both the steady and unsteady locomotion is the fact that the location of the maximal required strain doesn’t correspond with that of the maximal stress ($\bar{x} = 0.5 \rightarrow N\varphi =$...
At the location of maximal strain by steady swimming the DE-actuator has to exceed only 3/4 of this maximal stress ($\bar{\varepsilon} = 0.18 \Rightarrow N_{\varphi} = 63\ [N/m]$). On the other hand by unsteady swimming this advantage is less tangible. In fact at the locations of maximal strain ($\bar{\varepsilon} = 0.35$ and $\bar{\varepsilon} = 0.61$) the line loads amount to about $N_{\varphi} = 77\ [N/m]$ and $N_{\varphi} = 79\ [N/m]$. Nevertheless the larger stress requirement determined in the previous section is adopted.

The previously determined strain requirements are related to the skin length by non-bended state. The strains of DE-actuators are usually referred to the length by the non-activated equilibrium of forces ($L_0$). Thus, in order to evaluate the fulfillment of these conditions the skin strains have to be related to the non-activated DE-actuator length.

As previously highlighted the lateral strains on the convex and concave side have equal magnitude and opposite sign. Thus, compression and expansion strains are coupled. Fig. 2-10 illustrates schematically this protagonist-antagonist mechanism. The vertebral column is represented through a flexible joint. Thanks to a partial activation ($0 < U < U_{\text{max}}$) of both lightly elongated DE-actuators (in red), the non-bended state of the blimp can be achieved. The actuator length ($L$) by this partially activated state is equal to $L_1$. Starting from this partially activated state it is possible to bend the blimp body through the coupled activation-deactivation of the actuators. The actuator on the convex body side is fully activated ($L = L_2$: fully-elongated state) with the maximal voltage $U_{\text{max}}$, while the actuator on the concave side is fully deactivated ($U = 0$) and achieves its non-activated equilibrium state ($L = L_0$).

Fig. 2-10: Protagonist-antagonist mechanism (dorsal view) based on DE actuators (in red).
The strains of the actuators positioned on the convex ($\varepsilon_{12}$: strain between states 1-2) and concave ($\varepsilon_{10}$: strain between states 1-0) side related to the skin length by non-bended body state are so defined:

$$\varepsilon_{12} = \frac{L_0 - L_1}{L_1} = \frac{\Delta L}{L_1} \tag{25}$$

$$\varepsilon_{10} = \frac{L_0 - L_1}{L_1} = \frac{-\Delta L}{L_1} \tag{26}$$

$\varepsilon_{12}$ [-] Strain of the convex side related to the skin length by non-bended body state

$\varepsilon_{10}$ [-] Strain of the concave side related to the skin length by non-bended body state

$L_0$ [m] Actuator length by non-activated state

$L_1$ [m] Actuator length by partially activated state

$L_2$ [m] Actuator length by fully activated state

At this point it is possible to express the skin strains in relation to the actuator length at non-activated equilibrium ($L_0$). It follows

$$\varepsilon_{01} = -\frac{\varepsilon_{10}}{\varepsilon_{10} + 1} \tag{27}$$

$$\varepsilon_{02} = \varepsilon_\varphi = \frac{\varepsilon_{12} - \varepsilon_{10}}{\varepsilon_{10} + 1} = -\frac{2 \cdot \varepsilon_{10}}{\varepsilon_{10} + 1} \tag{28}$$

$\varepsilon_{01}$ [-] DE-actuator strain in longitudinal direction related to the actuator length at non-activated equilibrium needed to achieve the non-bended body state

$\varepsilon_{02}, \varepsilon_\varphi$ [-] DE actuator strain in longitudinal direction related to the actuator length at non-activated equilibrium needed to achieve the fully bended state

Therefore, the previously determined skin strains for steady and unsteady swimming can be now converted:

$$\varepsilon_{01}(\varepsilon_{10} = -7\%) = 7.52\%$$

$$\varepsilon_{02}(\varepsilon_{10} = -7\%, \varepsilon_{12} = +7\%) = \varepsilon_\varphi = 15.05\%$$

$$\varepsilon_{01}(\varepsilon_{10} = -35.5\%) = 55.04\%$$

$$\varepsilon_{02}(\varepsilon_{10} = -35.5\%, \varepsilon_{12} = +35.5\%) = \varepsilon_\varphi = 107.7\%$$

Noteworthy are the remarkably augmented strain requirements for the unsteady swimming.
2.3 Estimation of the Required Strain Rates

Since the blimp is not provided with an internal vertebral column, the DE-actuators positioned on the lateral sides of the blimp envelope must be activated simultaneously and with a time shift of half period ($\tau/2$) (see Fig. 2-11). As a consequence each actuator has to be activated with the tail-beat frequency. The adoption of this activation strategy allows to simulate the presence of the backbone and consequently to imitate accurately the trout motion.

![Fig. 2-11: Tail amplitude and activation voltage as a function of the time.](image)

Therefore, the strain rate requirements (summarized in Tab. 2-2) are defined by the trout tail-beat frequency for steady and unsteady swimming and the respective maximal lateral strains. The tail-beat frequency for the blimp is obtained by equalizing the Strouhal number of a trout in water with that of blimp in air.

<table>
<thead>
<tr>
<th>Tail-Beat Frequency</th>
<th>Period</th>
<th>$\varepsilon_{\phi,\text{max}}$</th>
<th>$\dot{\varepsilon}_{\phi,\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trout [Hz]</td>
<td>Blimp [Hz]</td>
<td>Blimp [s]</td>
<td>[%]</td>
</tr>
<tr>
<td>Steady 4.5</td>
<td>0.193</td>
<td>5.18</td>
<td>7.52</td>
</tr>
<tr>
<td>Unsteady 19</td>
<td>0.813</td>
<td>1.23</td>
<td>107.7</td>
</tr>
</tbody>
</table>

Tab. 2-2: Strain rate requirements.

The dielectric material is viscoelastic. Therefore, part of the deformation energy introduced under activation into a DE actuator is lost by internal dissipation [15]. Thus, it is important that the dissipated energy for the
specified activation frequencies \((f_{\text{steady}} = 0.193 \, [Hz], f_{\text{unsteady}} = 0.813 \, [Hz])\) doesn’t compromise the achievement of the required strain rate performances.

### 2.4 Requirement List for the Active Envelope

In Tab. 2-3 the requirements for an active envelope are listed. The requirements are divided in three main categories:

- **Blimp Envelope**
- **DE-Actuator**
- **Active Envelope**

The requirements can be fix (F) or tolerant (T). Differently from the fix requirements, which must be completely fulfilled, the tolerant ones can be met more or less. Since the stress for the DE-actuator, the strain and strain rates for the active envelope are the most important requirements, they will determine the feasibility of the proposed solution for an active envelope (see section 1.7). The proposed requirement list must not be considered as definitive. At this stage of the EAP-Blimp project it will be adopted mainly for the definition of a functional model for a segment of active envelope (see chapter 4) and for the evaluation of the experimental characterization (see chapter 5).

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Range</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blimp Envelope</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Mechanical Strength | The blimp envelope material can support the mechanical stresses induced by the internal pressure. | \(\Delta p = 600 \, [Pa]\), \[
\sigma_{x,\text{max}} = 6.48 \, [MPa]
\]
\[
\sigma_{y,\text{max}} = 12.75 \, [MPa]
\]| F               |
<p>| Tensile Stiffness   | The tensile stiffness is greater than that of the dielectric material.       | More than 3 order of magnitude            | F               |
| Compressive Compliance | The envelope can easily wrinkle under the action of compressive forces. The thickness of the material must be smaller as possible. | Thickness ( t &lt; 50 , [\mu m] ) | F               |
| Helium permeability | The envelope is tight to helium.                                              | Permeability (&lt; 1 , \left[ \frac{\text{litre}}{\text{m}^2 \cdot \text{day}} \right] ) | F               |</p>
<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
<th>Equation/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weldability</td>
<td>The envelope material is weldable.</td>
<td>F</td>
</tr>
<tr>
<td>Adhesiveness</td>
<td>The envelope material guarantees a good adhesion of the DE-actuator. The adhesive interface can support the shear stresses between the stretched dielectric material and the envelope.</td>
<td>Maximal Shear Stress $\tau_{\text{max}} = 13.5 , [kPa]$ (see section 4.5)</td>
</tr>
<tr>
<td>Chemical Compatibility</td>
<td>The envelope material and the DE-actuator are chemically compatible. The VHB4910 doesn’t corrode or alter the envelope material.</td>
<td>F</td>
</tr>
<tr>
<td>Humidity Absorption</td>
<td>The absorption of humidity is negligible.</td>
<td>T</td>
</tr>
<tr>
<td>Solar Radiation Proof</td>
<td>The material is proof to solar radiation.</td>
<td>T</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>The envelope material is electrically conductive. The electrical activation of the DE-electrodes in direct contact with the conductive envelope is possible.</td>
<td>T</td>
</tr>
</tbody>
</table>

**DE Actuator**

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
<th>Equation/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>The dielectric material consists of the dielectric film VHB4910 or VHB4905. Modification of this material through post-curing processes is admitted. The electrodes are compliant, thin and electrically conductive.</td>
<td>F</td>
</tr>
<tr>
<td>Stress</td>
<td>The dielectric actuator is able to support and to exceed the mechanical stresses of the envelope induced by the internal pressure. The needed forces can be achieved through the stacking of several DE-actuators.</td>
<td>$N_\theta (\Delta p = 300 , Pa) = 80 , N/m$</td>
</tr>
</tbody>
</table>

|  |  |
|  |  |
|  |  |
### Active Envelope

<table>
<thead>
<tr>
<th>Structure</th>
<th>The DE-actuator is attached directly on the tight envelope. The electrical connection of the DE-actuators can be achieved through external electrical contacts.</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain</td>
<td>The active envelope can achieve the required lateral strains needed to transpose the trout motion to the blimp. Steady Swimming: $\varepsilon_{\varphi} = 15.05%$ Unsteady Swimming: $\varepsilon_{\varphi} = 107.7%$</td>
<td>F T</td>
</tr>
<tr>
<td>Strain Rate</td>
<td>The active envelope can achieve the required lateral strain rates needed to transpose the trout motion to the blimp. The dissipated deformation energy doesn’t compromise the required performances. Steady Swimming: $\dot{\varepsilon}<em>{\varphi} = 1.45%/s$ Unsteady Swimming: $\dot{\varepsilon}</em>{\varphi} = 87.56%/s$</td>
<td>F T</td>
</tr>
</tbody>
</table>
| Manufacturing | - The manufacturing process is simple and not dangerous  
- Good reproducibility | F T |
| Inflammability | The active envelope is not inflammable or adequate measures are taken in order to reduce the fire hazard. | T |
| Weight Per Unit Area | The weight-per-unit-area of the active envelope is low as possible. The total weight of the active envelope doesn’t compromise the blimp buoyancy. $M_{tot} < 50\%$ of the payload | T |

Tab. 2-3: Requirement list for the active envelope.
3 Theoretical Feasibility

In this chapter the theoretical feasibility of the proposed solution for an active envelope is investigated. In particular the mechanical behavior of the stretched DE-actuators under the action of the blimp envelope stresses due to the internal pressure is analyzed. Then, the fulfillment of the dynamical requirements is examined through the strain analysis of DE-circle actuators under cyclic electrical activation. At the end of this chapter the required active area and the resulting total active envelope weight are estimated.

3.1 Stress and Strain Analysis of the DE-Actuator

In order to evaluate the theoretical fulfillment of the mechanical stress (\(N_\phi(\Delta p = 300 [Pa]) = 80 [N/m]\) and \(N_\theta(\Delta p = 300 [Pa]) = 160 [N/m]\)) and strain (steady swimming: \(\varepsilon_\phi = 15.05 [%]\); unsteady swimming: \(\varepsilon_\phi = 107.7 [%]\)) requirements a hyperelastic material model for the DE-actuator is implemented. Before proceeding with the model description, the stretched states of the DE-actuator and a quasi-static model of the active envelope are discussed in the next two sections.

3.1.1 Stretched, Over-Stretched, Pre-Stretched and Activated States

As explained in section 1.6.1 the stretching procedure is justified by equation (4). The stretching ratio of the dielectric film is defined as:

\[
\lambda = \frac{L}{L_{\text{ORIGIN}}} = \varepsilon + 1
\]  

(29)

\(\lambda\) [-] Stretching ratio  
\(L\) [m] Actual length of the stretched dielectric film  
\(L_{\text{ORIGIN}}\) [m] Original length of the non-stretched dielectric film  
\(\varepsilon\) [-] Strain related to the original (non-stretched) dielectric film length

As anticipated in section 1.7, during the manufacturing process the stretched DE-actuator is applied to the tight blimp envelope (fully elongated state of the envelope). The stretching procedure and the stretched state of the dielectric film by the mounting of the actuator are defined as over-stretching
procedure and over-stretched state \((\lambda_{x,OVER}, \lambda_{y,OVER})\) respectively (see Fig. 3-1). If the forces exerted by the over-stretched DE are larger than that due to the internal pressure, the blimp envelope segment wrinkles till a non-activated equilibrium of forces is achieved. This phenomenon is called partial relaxation. The stretched state of the dielectric film by the non-activated equilibrium of forces is defined as pre-stretched or non-activated state \((\lambda_{x}(U=0), \lambda_{y}(U=0))\). Through the electrical activation \((U > 0)\) of the DE-actuator the blimp envelope can regain partially (Fig. 3-1: \(U = U_1\)) or completely (Fig. 3-1: \(U = U_2 > U_1\)) the original tight and fully-elongated state. The stretched state of the dielectric film by the activated equilibrium of forces is identified as activated state \((\lambda_{x}(U>0), \lambda_{y}(U>0))\).

![Fig. 3-1: Over-stretched, pre-stretched and activated DE states.](image)

### 3.1.2 Quasi-Static Model of the Active Envelope

The active envelope composed of at least a DE actuator attached to a blimp envelope segment can be modelled as a spring and a rigid element in parallel representing the DE actuator and the blimp envelope segment respectively (see Fig. 3-2). This model is adequate only for the description of the quasi-static mechanical behaviour of the active envelope. As the blimp envelope can wrinkle under compressive forces exerted by the DE it is represented by a blocking mechanism (Fig. 3-2 a), which is able to carry forces only in its stroke position. This parallel connection is in series with two rigid elements, which represent the envelope material located on both sides of the DE actuator. If the forces exerted by the DE are larger than that induced by the internal pressure, the blimp envelope will wrinkle till a non-activated equilibrium of forces is achieved. Since a wrinkled membrane is not able to carry loads perpendicularly to the wrinkle direction, the forces are supported exclusively by the DE actuator (Fig. 3-2 a). By increasing the internal pressure the mechanical loads in the envelope will exceed that induced by the stretched dielectric elastomer. Thus, the blimp envelope segment will reach its fully elongated state (the blocking mechanism...
reaches its stroke position) (Fig. 3-2 b). Since the stiffness of the blimp envelope is 5 order of magnitude larger than that of the acrylic material (VHB4910: \( E = 3.5 \cdot 10^2 \) [MPa]; non-fiber-reinforced envelope material: \( E = 1-3 \) [GPa]), the load will be transferred primarily through the blimp envelope. The active envelope segment can achieve its fully elongated state through the electrical activation of the actuator as well. Also in this case the mechanical loads are supported exclusively by the blimp envelope.

![Diagram of load transfer in the active envelope](image)

**Fig. 3-2:** Load transfer in the active envelope: (a) wrinkled blimp envelope: the load induced by the internal pressure is supported by the DE actuator; (b) active envelope in its fully elongated state: the load induced by the internal pressure is supported by the tight blimp envelope.

The diagram in Fig. 3-3 shows the force-displacement curve for the active envelope for its non-activated (black line) and activated state (red line), where the force is given by the internal pressure. The displacement \( \Delta x \) is meant as difference between the fully elongated state and the actual one of the active envelope segment. The diagram is obtained from the previous model (Fig. 3-2). In fact by positive displacement differences \( \Delta x > 0 \) the stiffness of the fully elongated envelope prevails over that of the DE (Fig. 3-2 b), which becomes predominant again when the blimp envelope wrinkles \( \Delta x < 0 \) (Fig. 3-2 a). The manufacturing process of the active envelope proposed in section 1.7 consists of the application of an over-stretched DE-actuator to the tight envelope (Fig. 3-3 1) (e.g.: the over-stretching conditions of the dielectric film are \( (\lambda_x,OVER, \lambda_y,OVER) = (5, 5) \); the \( x \)- and \( y \)-directions of the DE-actuator correspond to the longitudinal \( (\phi) \) and transversal ones \( (\theta) \) of the blimp; for this example the following two assumptions are valid: (1) line load ratio \( N_{\theta}/N_{\phi} = 2 \), (2) the resulting force exerted by the dielectric film in \( y \)-direction is equal to the envelope one in \( \theta \)-direction. Since a line load ratio \( N_{\theta}/N_{\phi} = 2 \) is assumed, the symmetrically over-stretched dielectric film exerts larger forces in \( x \)-direction than that induced in the envelope by the internal pressure. Thus, the actuator is subjected to a partial relaxation in \( x \)-direction (the blimp envelope wrinkles in \( \phi \)-direction, while it keeps its tight state in \( \theta \)-direction) till a non-activated equilibrium of forces is reached (Fig. 3-3 2). The pre-stretching conditions are now \( (\lambda_x(U=0), \lambda_y(U=0)) = (3.7, 5) \). The electrical activation of the pre-stretched DE-actuator leads to an activated equilibrium state (Fig. 3-3 3) \( (\lambda_x(U>0), \lambda_y(U>0)) = (4.6, 5) \). The activation strain \( \varepsilon_a(U) = 25 \% \) between
the non-activated equilibrium (Fig. 3-3 2) and the activated one (Fig. 3-3 3) is related to the actuator length at non-activated equilibrium. This strain can be defined as a function of the stretching ratios by non-activated and activated equilibrium states:

\[ \varepsilon(U) = \frac{\lambda(U > 0)}{\lambda(U = 0)} - 1 \]  

\( \varepsilon(U) \) [-] Activation strain related to the actuator length at non-activated equilibrium state between the pre-stretched and the activated dielectric film states  
\( \lambda(U=0) \) [-] Stretching ratio by non-activated equilibrium state related to the original (non-stretched) dielectric film length  
\( \lambda(U>0) \) [-] Stretching ratio by activated equilibrium state related to the original (non-stretched) dielectric film length

By increasing the internal pressure, the activated equilibrium state is shifted till reaching the fully elongated state of the blimp envelope (Fig. 3-3 4), from which the blimp envelop stiffness prevails over the dielectric film one (Fig. 3-2 b). By changing the activation voltage and the boundary conditions, all states in the shaded area of the force-displacement diagram can be reached.

The over-stretched state of the DE-actuator determines the amount of the partial relaxation before the achievement of a non-activated equilibrium.
state. The partial relaxation can lead to three characteristic pre-stretched states, which are illustrated in the force-displacement diagram of Fig. 3-4. The activation of the pre-stretched DE-actuator in 2a (Fig. 3-4) doesn’t lead to the fully elongated state of the blimp envelope. Since the activation strain is not blocked by the envelope, it defined as free activation strain. In this case the partial relaxation of the DE-actuator is not compensated through the electrical activation. Thus, the fully elongated state of the blimp envelope can be reached through the increment of the activation voltage. The activation strain of a pre-stretched DE-actuator in 2c (Fig. 3-4) not only can compensate the envelope contraction due to the partial relaxation of the DE-actuator, but it is blocked by the blimp envelope after reaching its fully elongated state. The ideal pre-stretched state is in 2b (Fig. 3-4). In fact the electrical activation of the DE-actuator allows to reach the fully elongated state of the blimp envelope without impeding the achievement of the maximal activation strain.

![Force displacement diagram](image)

Fig. 3-4: Force displacement diagram; (2a-3a) free activation strain; (2b-3b) free activation strain: ideal case where the partial relaxation is entirely compensated by the electrical activation; (2c-3c) blocked activation strain.

The over-stretching strategy allows to obtain the desired contraction of the blimp envelope. On the other hand it doesn’t assure the achievement of the required strains through the electrical activation. In other words the pre-stretching conditions at non-activated equilibrium have to be such as the partial relaxation can be compensated through the electrical activation (Fig. 3-4 2b-3b).

A possible and intuitive strategy to determine adequately the over-stretching conditions of the dielectric film is schematically illustrates in Fig. 3-5 and explained in the last part of this section.
The resulting line loads for a specific envelope location and internal pressure is determined thanks to the Timoshenko’s theory (see section 2.1.2). According to the spring-rigid-element model, if the dielectric film reaches the non-activated equilibrium state by wrinkling the blimp envelope, it will support the local resulting force per unit length ($N_x = N_\phi$ and $N_y = N_\theta$).

Starting from the line loads, it is possible to determine the corresponding pre-stretching conditions of the dielectric film through an adequate theoretical model for the DE-actuator mechanical behaviour. This model is successively used to predict the achievable activation strains ($\varepsilon_x(U)$ and $\varepsilon_y(U)$). At this point the activation strain and the pre-stretching conditions of the dielectric film allow through equation (30) to calculate the required over-stretching conditions.

### 3.1.3 Modeling of the DE-Actuator Based on a Hyperelastic Model

The dimensioning strategy for the determination of the over-stretching conditions proposed in the previous section (see also Fig. 3-5) needs an adequate model that allows the estimation of the non-activated and activated film stretching conditions as a function of the resulting line loads and the applied electrical voltage. The author adopts a hyperelastic film model developed by Lochmatter [26], which considers the two main characteristics of dielectric elastomer films:

a. hyperelastic material characteristics in all three-space directions
b. mechanical coupling of the spatial deformations based on the incompressibility condition for soft elastomers.

The model provides a set of four equations for the description of the mechanical stress versus stretching conditions of the hyperelastic dielectric film:

\[
\sigma_i = K_i \cdot \lambda_i \cdot (\lambda_i - 1) - p, \quad i = x, y, z \quad (31)
\]

\[
\lambda_x \cdot \lambda_y \cdot \lambda_z = 1 \quad (32)
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_i$</td>
<td>[Pa]</td>
<td>Mechanical stress in i-direction</td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>[-]</td>
<td>Stretching ratio in i-direction</td>
</tr>
<tr>
<td>$K_i$</td>
<td>[Pa]</td>
<td>Stiffness of the dielectric film VHB4910</td>
</tr>
</tbody>
</table>
Hydrostatic pressure

Lochmatter found a good match between the experimental tensile test of VHB4910 and the film model for a stiffness of \( K \approx 3.50 \times 10^{-2} \) [MPa]. Furthermore this hyperelastic model allows to consider the electromechanical coupling, which is achieved by introducing the equivalent electrode pressure in the film thickness direction (Eq. 33).

\[
\sigma_z = -p_{\text{equivalent}} = -\varepsilon_0 \cdot \varepsilon_r \cdot \left( \frac{U}{L_z^{(0)}} \right)^2 \cdot \frac{1}{\lambda_z^2}
\]  

(33)

\( \sigma_z \) [Pa] Mechanical stress in film thickness direction
\( p_{\text{equivalent}} \) [Pa] Equivalent electrode pressure
\( \varepsilon_0 \) \[\frac{A \cdot s}{V \cdot m}\] Free space permittivity
\( \varepsilon_r \) [-] Relative permittivity of the dielectric film VHB4910
\( U \) [V] Voltage
\( L_z^{(0)} \) [m] Original film thickness \( (L_z^{(0)} = 1 \text{ [mm]}) \)
\( \lambda_z \) [-] Stretching ratio in film thickness direction

This hyperelastic model allows only the investigation of DE actuators that have an activation strain rate of \((d\lambda/dt) \approx 2 \%/s\), which corresponds to a quasi-static activation cycle. Thus, it is inadequate to examine the fulfillment of the strain rate requirements.

The set of four equations was solved numerically with Mathematica 5 (see Documentation CD: “Hyperelastic Film Model.nb”). The equations were inserted and solved in a FOR-cycle, in which at the end of each loop the mechanical stresses \( \sigma_x \) and \( \sigma_y \) were incremented by keeping a membrane stress ratio of 2 or 1.5 (only the most representative line load ratios of the blimp envelope were examined) and the resulting stretching ratios for a specific voltage extracted. The results were evaluated with Microsoft Excel, where the mechanical stresses were converted in forces per unit length (see Documentation CD: “Stress Ratio 2.xls” and “Stress Ratio 1.5.xls”). The stretching ratios \( \lambda_x \) and \( \lambda_y \) as functions of the mechanical line loads are shown in Fig. 3-6 (line load ratio \( N_\theta/N_\phi = 2 \)) and in Fig. 3-7 (line load ratio \( N_\theta/N_\phi = 1.5 \)). By increasing the voltage, the line load needed to keep constant the stretching condition of the film decreases. Furthermore, the model predicts for voltages above 1.5 \([kV]\) two activated equilibrium states for each line load – a stable (inferior) one and an unstable (superior) one. These activated equilibrium states converge to a critical point, which represents the collapse of the film in the thickness direction. Thus, only the inferior activated equilibrium states have to be considered. Furthermore, Fig. 3-6 and Fig. 3-7 show that by a line load ratio \( N_\theta/N_\phi = 1.5 \) the forces per unit length needed to achieve a specific stretched state are higher than the ones by a line load ratio \( N_\theta/N_\phi = 2 \).
By $N_x = 19 \, [N/m]$ and $N_y = 38 \, [N/m]$ the dielectric film presents a pre-stretched state of about $\lambda_x = 3.15$ and $\lambda_y = 4.22$ (see Fig. 3-6). An activation of 1.5 $[kV]$ leads to an activated state of about $\lambda_x = 4.24$ and $\lambda_y = 5.63$. The activation strains between the pre-stretched and activated states are $\varepsilon_x(U) = 34.6 \,[\%]$ and $\varepsilon_y(U) = 33.4 \,[\%]$ respectively. The one in $x$-direction fulfills abundantly the strain requirement of 15.05 $[\%]$. Furthermore, a stacking of only four actuators is able to overcome the force per unit length requirements defined in section 2.1.2.

Fig. 3-6: Stretching ratios as a function of the resulting line loads and applied voltage (line load ratio $N_y/N_x = 2$).

Fig. 3-7: Stretching ratios as a function of the resulting line loads and applied voltage (line load ratio $N_y/N_x = 1.5$).

Since the strain in $y$-direction ($\theta$- direction of the blimp) is not required, it should be avoided. If the active envelope reaches the fully-elongated state in $y$-direction already by the non-activated equilibrium state, an activation of the DE-actuator leads to a maximized elongation in $x$-direction ($\phi$-direction of the blimp) and to a blocked strain in $y$-direction.
3.1.4 Modeling of the Active Envelope Based on a Hyperelastic Model

The main limit of the implementation of the hyperelastic model proposed in section 3.1.3 is that the blocking action of the blimp envelope by achievement of an activated fully elongated state is not considered. In other words, the activation of the pre-stretched DE-actuator could lead to a higher elongation than that allowed by the envelope. Furthermore, the maximization of the longitudinal elongation through the blocking of the transversal one wasn’t taken into account. The blocking action of the envelope and the maximization of the longitudinal strain can be implemented through the following approach.

The line loads \((N_x,OVER, N_y,OVER)\) needed to keep passively constant a specific biaxial over-stretching condition \((\lambda_{x,OVER}, \lambda_{y,OVER})\) are determined. Then, the over-stretching ratio \(\lambda_y\) is kept constant \((\lambda_y(U=0) = \lambda_{y,OVER})\), while the line load in \(N_x\) is progressively reduced \((N_x(U=0) = N_x,OVER - \Delta N_x)\) by preserving a line load ratios \(N_y/N_x = 2\). This strategy allows to contract the blimp envelope in \(\phi\)-direction and at the same time to maximize the longitudinal activation strain \(\varepsilon_x(U)\) (the strain in \(\theta\)-direction is blocked). The resulting pre-stretching ratio at non-activated equilibrium \(\lambda_x(U=0)\) and the line load \(N_y(U=0)\) are calculated.

Starting from the non-activated state and by keeping \(\lambda_y\) constant, the resulting stretched state \(\lambda_x(U>0)\) due to the electrical activation can be determined. If \(\lambda_x(U>0)\) is larger than \(\lambda_{x,OVER}\), it means that the elongation of the DE-actuator is blocked by the blimp envelope. In this case \(\lambda_x(U>0)\) is set equal to \(\lambda_{x,OVER}\). The activation strain between the pre-stretched state and the activated one can be calculated thanks to equation (30). The entire algorithm (see Fig. 3-8) was solved with Mathematica 5 (see Documentation CD: “Active Envelope Model.nb”).

**Fig. 3-8:** Algorithm for the active envelope model.

Fig. 3-9 shows the maximal achievable activation strain in \(x\)-direction (longitudinal blimp direction) as a function of the over-stretching conditions for an activation voltage of 3.5 \([kV]\) and a line load ratios \(N_y/N_x = 2\).
Fig. 3-9: Activation strain $\varepsilon_x(U)$ in $x$-direction (longitudinal blimp direction) as a function of the over-stretching conditions ($U = 3.5 \text{ [kV]}$, $N_y/N_x = 2$).

Fig. 3-10 illustrates the contour plot of the previous graph (Fig. 3-9), where the black lines represent points of equal activation strain $\varepsilon_x(U)$. Kessler and Iseli showed in their semester thesis [27] that the product of the stretching ratios should not exceed a value of about $\lambda_x \lambda_y = 20$. The blue line in Fig. 3-10 shows the over-stretched states that respect this condition, while the red one correspond to biaxially over-stretched states that were experimentally characterized. The green-shaded area includes all over-stretched states, for which the activation strain is not blocked by the blimp envelope. The over-stretched states in the yellow-shaded area lead to activation strains, which are blocked by the blimp envelope. The over-stretched states located in the red-shaded area cause the mechanical failure of the dielectric film. The boundary line between the yellow-shaded area and the green-shaded one stands for ideal over-stretched states that can compensate the partial relaxation of the blimp envelope through the electrical activation ($U = 3.5 \text{ [kV]}$) (partial relaxation: Fig. 3-3 1-2; activation Fig. 3-3 2-3). An ideal over-stretched state could be for instance $(\lambda_x, \lambda_y) = (4.5, 4.5)$, which provides an activation strain $\varepsilon_x(U)$ of about 26.36 $\%$, which fulfills abundantly the strain requirement for steady swimming. In order to predict the fulfillment of the line load requirement ($N_y = 80 \text{ [N/m]}$), the force per unit length exerted by the DE-actuator after the achievement of the pre-stretched state must be considered. The stacking of only four DE-actuators allows to fulfill this condition ($N_y = 80 \text{ [N/m]}$; $\lambda = 4.5 \rightarrow N = 20 \text{ [N/m]}$). Tab. 3-1 highlights that the symmetrically over-stretched states provide higher activation strains but exert lower forces per unit length in longitudinal direction. On the other hand, the asymmetrically over-stretched states guarantee high forces per unit length but achieve lower activation strains. A possible solution of this dilemma could be firstly the stacking of several actuators and secondly the augmentation of the applied electrical voltage.
Even tough the model shows very promising results, an experimental characterization of the active envelope is required. Indeed the assumption of the blocked strain in $y$-direction must be demonstrated. In fact, even though the envelope is fully elongated in this direction, this doesn’t impede necessarily the wrinkling of the DE-actuator due to the electrical activation. The proposed model of the active envelope could become a very useful and powerful tool for the estimation of the required over-stretching film conditions by fitting it to the experimentally obtained results.

### 3.2 Strain Rate Analysis of the DE-Actuator

In order to investigate the fulfillment of the strain rate requirements a model developed by Wissler [28] for the characterization of the dynamical behavior of DE-circle-actuator was adopted.

The circle actuator is a very simple configuration, which consists of a radially stretched film spanned on a rigid circular frame. The active zone is a circular area in the centre of the dielectric film, which is coated double-sided with a compliant electrode. The passive film belt around the active
area can be considered to act as an elastic boundary condition for stretching the active zone in radial direction. Under electrical activation the active zone elongates and the passive film belt relaxes radially. When short-circuiting the actuator the active zone contracts radially and stretches thereby the passive film belt [15].

![Circle actuator](image)

Fig. 3-11: Circle actuator (left) with active zone in deactivated (centre) and activated state (right) [15].

The model defines the strain energy function through the hyperelastic model of Yeoh:

$$W = C_{10} \left( \lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3 \right) + C_{20} \left( \lambda_1^4 + \lambda_2^4 + \lambda_3^4 - 3 \right) + C_{30} \left( \lambda_1^6 + \lambda_2^6 + \lambda_3^6 - 3 \right)$$

(34)

$$W$$ Strain energy function

$C_{10}, C_{20}, C_{30}$ Material parameters

The time-dependency of the parameter is considered through the Prony series. Then, the resulting strain energy function is implemented in ABAQUS.

The results for a sinusoidal activation voltage ($U_{\text{max}} = 3.5 \ [kV]$) with the frequencies of the steady ($f = 0.193 \ [Hz]$) and unsteady swimming ($f = 0.813 \ [Hz]$) are illustrated in Fig. 3-12 and Fig. 3-13. The activation at lower frequencies allows the circle-actuator to achieve already by the first activation cycles the maximal radial strain of about 9 [%]. The difference between maximal and minimal strains is kept constant and amounts to about 7 [%].
The sinusoidal activation at the frequency of unsteady swimming shows a slower achievement of the maximal strain. Analogously to the previous case the difference between maximal and minimal strain is constant over the time and is approximately 4.5 [%].

Since the radial strain is always in phase with the activation voltage signal for both activation frequencies (and even for higher activation frequencies: see Fig. 3-14; $f = 1.626 \ [Hz]$), it can be concluded that the DE-actuator should be able to fulfill the dynamic requirements imposed by the fish-like
locomotion. On the other hand it is not clear how good the results obtained for a circle-actuator can be transposed to a planar one, which presents different boundary conditions. Furthermore, since the radial strains of the circle-actuator are smaller than the typical ones of a planar DE-actuator, it is impossible to evaluate the fulfillment of the strain rate requirements. Thus, an experimental characterization of the active envelope is necessary.

![Graph](image)

Fig. 3-14: Strain as a function of the time; $f = 1.626 \text{ [Hz]}$.

### 3.3 Estimation of the Required Active Area and of the Total Active Envelope Weight

The active area and the total active envelope weight are here determined by considering the needed mechanical power required to achieve a stationary cruising speed of 1.03 [m/s] (steady swimming).

A trout swimming at stationary speed must exert a thrust force equal to its drag force (for the complete calculation see Documentation CD: “Estimation of the Active Surface.xls”):

$$F_{T,T_{\text{Trout}}} = F_{D,T_{\text{Trout}}} = \frac{\rho_{\text{Water}}}{2} \cdot C_{D,\text{Trout}} \cdot A_{F,T_{\text{Trout}}} \cdot V_{T_{\text{Trout}}}^2 = 0.008557 \text{ [N]} \quad (35)$$

The thrust force of the blimp is analogously defined:

$$F_{T,B_{\text{lim}}p} = F_{D,B_{\text{lim}}p} = \frac{\rho_{\text{Air}}}{2} \cdot C_{D,\text{B}_{\text{lim}}p} \cdot A_{F,B_{\text{lim}}p} \cdot V_{B_{\text{lim}}p}^2 \quad (36)$$

$F_{T,T_{\text{Trout}}} \quad \text{[N]} \quad \text{Thrust force of the trout}$
The thrust force of the blimp is:

\[ F_{T,Blimp} = \frac{C_{DF,Blimp}}{C_{DF,Trout}} \cdot \frac{\rho_{air}}{\rho_{water}} \cdot \frac{A_{r,Blimp}}{A_{r,Trout}} \cdot F_{T,Trout} = 0.07529 \text{ [N]} \]  

The resulting power for the blimp is:

\[ P_{T,Blimp} = F_{T,Blimp} \cdot v_{Blimp} = 0.07736 \text{ [W]} \]  

By dividing equation (38) with the power of unit area of a spring roll DE actuator [29], the needed active area can be determined. Spring roll DE-actuators are constituted by dielectric film coated double-sided with a compliant electrode and rolled up around a compressed cylindrical spring, which keeps the dielectric film pre-stretched. Furthermore, the electromechanical efficiency of the actuators and the mechanical-fluidodynamical efficiency have to be considered. Thus, the total active area amounts to

\[ A_{Active} = \frac{P_{T,Blimp}}{P_{SR,DE} \cdot \eta_{E-M} \cdot \eta_{M-F}} = 16.13 \text{ [m}^2\text{]} \]  
The required active area is about the 51 [%] of the total blimp envelope surface. The estimated total weight of the active envelope is 0.83 kg, which corresponds to about 22.6 [%] of the total lifting force provided by the helium. Fig. 3-15 shows the achievable cruising speed as a function of the \( \frac{A_{\text{Active}}}{A_{\text{Blimp}}} \) ratio, where \( A_{\text{Blimp}} \) is total blimp envelope surface. Noteworthy is the fact that the substantial increments of the \( \frac{A_{\text{Active}}}{A_{\text{Blimp}}} \) ratio don’t lead to significant increments of the cruising speed (Fig. 3-15 on the right). The most important limiting factors for the maximal cruising speed are the efficiency of the DE-actuators and the volume related drag coefficient. The adopted electromechanical efficiency is quite conservative. However the required cruising speed of 1.03 \([m/s]\) and the total weight of the active envelope fulfills the requirement of section 2.4.

Unfortunately the energetic based calculation doesn’t consider for instance the additional weight of the electronic circuitry or the stacking of DE-actuators needed to exceed the envelope forces. Thus, the effective total active area and weight could be higher. Therefore, the proposed estimation has to be considered only indicative of the real fulfillment of the weight requirement.

\[
A_{\text{Active}} \quad [m^2] \quad \text{Active area}
\]
\[
P_{SR,DE}^* \quad [W/m^2] \quad \text{Power per unit area of the spring roll DE actuator}
\]
\[
(\lambda_x, \lambda_y) = (6.5, 3) [29]
\]
\[
\eta_{E-M} \quad [-] \quad \text{Electromechanical efficiency [29]}
\]
\[
\eta_{M-F} \quad [-] \quad \text{Mechanical-Fluidodynamical efficiency [12]}
\]
4 Experimental Feasibility

In this chapter the experimental feasibility of the proposed solution for an active envelope is investigated through the experimental characterization of a functional model. The experimental results are presented in chapter 5 and successively discussed in chapter 6.

4.1 Parameter Study

In this section the possible parameters that could influence the performance of the active envelope are determined. They will allow the definition of an adequate functional model and testing device for the experimental characterization of the active envelope as well as the planning of an adequate test procedure. The possible parameters are summarized in the following list:

- Biaxially applied mechanical loads
- Over-stretching conditions of the dielectric film
- Applied electrical voltage
- Number of layers (stacking of the actuators)
- Material (VHB4910, VHB4905, post-processed VHB4910)
- Mechanical properties of the envelope material (compression compliance)
- Manufacturing process of the DE-actuator
  - Electrode coating mixture
  - Coating technique of the DE-film
  - Electrical contacts
  - Electrode configuration
- Manufacturing process of the active envelope
- Adhesiveness interface between DE-actuator and blimp envelope
  - $A_{\text{Active}}/A_{\text{Total}}$ ratio of the DE-actuator
- Age of the DE-actuator

The listed parameters lead to an enormous variety of combinations, which can be reduced through the following considerations. The biaxially applied mechanical loads, the over-stretching conditions of the dielectric film and the applied electrical voltage can be considered the most important parameters. The mechanical loads combinations can be drastically reduced by assuming a linear elastic behavior of the dielectric film. Unfortunately this assumption can be applied only for quasi-static tensile tests ($\dot{\varepsilon} \leq 0.3\ [\%/s]$; Kobes [29]). Another possible reduction of the mechanical load steps could be achieved by considering exclusively the
typical line load ratios of the blimp envelope \((N_\theta/N_\phi = N_y/N_x \subset [1-2])\). Also this measure cannot be taken in account, since it would limit drastically the understanding of the mechanical behavior of the active envelope. On the other hand the number of over-stretching combinations can be reduced by taking into account biaxially over-stretched states, which guarantees good strain performances (Kessler and Iseli [27]: \(\lambda_x,\lambda_y \subset [15-20]\)). Since the reliability of the manually manufactured DE-actuators is still relatively low and the electrical breakdown risk relatively high, the electrical voltage can be limited to a single activation step at \(3.5 \text{ [kV]}\).

In his work, Romann [30] demonstrated that the stacking of several actuators leads to a linear scaling of the resulting biaxial forces. Thus, the experimental characterization can be limited to single layered actuators. Furthermore, the priority is given to the dielectric material VHB4910. The choice of the envelope material is here circumscribed to a modification of a commercially available helium tight material (NONEX Al+ 925: see section 8.3), which allows the fulfillment of the gas permeability requirement and at the same time of the compressive compliance thanks to its small thickness \((t = 25 \text{ [\mu m]})\).

In this feasibility study the parameters related to the manufacturing of the DE-actuator and the active envelope are not taken in account. Only a manufacturing strategy is considered that allows the achievement of a good reliability of the actuator (see section 8.1). Further optimizations of the manufacturing process and its influence on the active envelope performance could be topic of future works. The adhesive interface between DE-actuator and blimp envelope is limited to the uncoated area of the actuator side facing the envelope. A good adhesion between actuator and envelope allows a maximization of the \(A_{\text{Active}}/A_{\text{Total}}\) ratio by reducing the uncoated area needed for the adhesive interface. On the other hand actuators with high \(A_{\text{Active}}/A_{\text{Total}}\) ratio make the manual manufacturing process more difficult. Even though this parameter influences strongly the overall performances of the DE-actuator, only an \(A_{\text{Active}}/A_{\text{Total}}\) ratio determined through an adhesiveness test will be characterized. The influence of the actuators age will not be considered. Nevertheless, the maximal actuators age will be limited to seven days.

### 4.2 Design of a Functional Model and of a Biaxial Loading Device

The principle purpose of the active envelope functional model is the investigation of the stress, strain and strain rates requirements defined in section 2.4. The functional model must allow the characterization of the non-activated and activated mechanical behavior of the active envelope and the understanding of the mechanical interaction existing between DE-actuator and blimp envelope. These goals can be achieved through the simulation of the membrane stress states of a rotationally symmetric ellipsoidal shell due to internal pressure. The biaxial strains of the active envelope have to be determined as a function of:
a. the resulting biaxial forces or line loads \((F_x = F_\phi, F_y = F_\theta \text{ or } N_x = N_\phi, N_y = N_\theta)\)
b. the biaxial over-stretching film conditions \((\lambda_x,OVER = \lambda_\phi,OVER, \lambda_y,OVER = \lambda_\theta,OVER)\)
c. the applied voltage \((U = 3.5 \text{ [kV]})\)
d. the number of film layers (only single layered DE-actuator are characterized)
e. the dielectric material (VHB4910)
f. the envelope material (NONEX Al+ 925)

The functional model and the testing device proposed in this diploma thesis were obtained thanks to the method of the morphological box. The simplest technique to induce biaxial membrane stress states consists of applying in-plane loads along the perpendicular arm of a cruciform specimen (see Fig. 4-1). The DE-actuator is attached directly on the biaxially loaded zone.

![Cruciform functional model of the active envelope.](image)

In order to reduce the boundary effects, the four fastening elements for the load transmission must be located far away from the biaxially loaded zone. Besides, the shear stresses and the stress concentrations must be minimized. This allows to obtain a homogeneous stress state in the biaxially loaded zone of the cruciform specimen. This is not possible by using one actuator per loading direction. In fact, the centre of the specimen would move during a test causing side bending of the specimen. This would lead to non-symmetric strains and to shear stresses in the biaxially loaded zone (see Fig. 4-2b). Systems with two actuators per loading direction allow to keep the specimen centered (see Fig. 4-2a). Stress concentration can be reduced by adopting a rounded corner fillet at the intersection of the arms.

![Cruciform specimen with actuators: (a) four actuators; (b) two actuators [32].](image)
The blimp envelope is a modification of a commercially available helium tight material (NONEX Al+ 925). The composition is illustrated in Fig. 4-3. The adhesive layer is represented in gray. Polyamide constitutes the load bearing layer. The gas retention is guaranteed by the aluminum coating and the EVOH layer (Ethylene-Vinyl Alcohol Copolymer [41]). Polyurethane is used as environmental/weathering protection layer. The envelope weldability is obtained thanks to a polyethylene layer. The total film thickness amounts to about 25 $\mu$m.

![Composition of the NONEX AL+ 925.](image)

The employed dielectric material is the VHB4910 of the 3M company [40]. The compliant electrodes consist of a mixture of conductive material (Ketjenblack EC-300J [42]) and silicone. Since the adhesion interface between the sticky dielectric film and the polyurethane is quite strong, the DE-actuator is attached on the environmental/weathering protection layer of the envelope.

The design of a biaxial loading device is inspired by already existing biaxial creep testing machine. The simplest setups are based on ropes systems and deadweights [31]. In modern devices, the use of hydraulic actuators represents a very versatile technique for the application of biaxial loads [32].
The adopted solution (see Fig. 4-5) is similar to the plane biaxial test device of Fig. 4-4 a. The loads are transmitted to the specimen through ropes, which pass over pulleys. Balance pans connected to the extremity of each rope allow the application of weights. In order to change the applied load by keeping a stable position of the specimen, each rope pulley is equipped with a brake. The four white reference dots positioned at the corners of the DE-actuator allow a video extensometer to measure the biaxial strains.

The proposed cruciform functional model presents three main drawbacks. Firstly, it can only approximate the inhomogeneous membrane stress conditions of the blimp envelope. Secondly, only in an ideal situation no displacement of the centre point of the specimen can be observed (Fig. 4-6 a). Even though four actuators are used, a small displacement might occur in real situation (Fig. 4-6 b). This leads to an imbalance in the forces and for instance an additional load component is added in y-direction. The third drawback is due to deflection of the specimen, when small loads are applied. This situation leads to strain measurement errors. On the other hand
the cruciform functional model allows to determine easily the resulting biaxial forces in the active envelope segment.

![Fig. 4-6: Force on the cruciform specimen: (a) ideal situation; (b) real situation][32].

In Fig. 4-7 the three systems of coordinates adopted in this diploma thesis are illustrated. Capital $X$ and $Y$ are the semi-axis of the ellipsoid. Small $x$ and $y$ are the planar coordinates of the cruciform specimen that correspond locally to the membrane coordinate $\varphi$ (longitudinal) and $\theta$ (transversal) of the ellipsoidal blimp.

![Fig. 4-7: Coordinates systems.]

### 4.3 The Test Setup

The test setup is illustrated in Fig. 4-8. The cruciform functional model is positioned horizontally in the loading device and subjected to biaxial forces. A monochrome video extensometer camera (COSMICAR/PENTAX lens: 12 mm 1:1.2) is located perpendicular and centered over the DE-actuator (specimen-camera lens distance: 61 [cm]). A frame grabber interface card is fitted into the Video extensometer controlling PC and is connected to the camera via a flexible cable. The card converts the PAL video signal into an 8 Bit digital format while simultaneously generating a 640 x 480 pixel image on the colour monitor and operating under WindowsNT based software. The four white dots at the electrode corners allow the video extensometer to measure the biaxial strains (Dotmeasurement for Window; MESSPHYSIK Materials Testing). A second computer provides thanks to a LabVIEW based program (AWC.vi) the input signal for the high voltage source (TREK Model 5/8 [43] Fig. 4-9). The board NI 6030E from National
Instruments is used as data acquisition hardware. This board is combined with LabVIEW, which allows to design measurement and control applications. One analog output is needed as control signal to the high-voltage amplifier (TREK). An analog input is used to measure the high-voltage produced by the TREK. The DE-actuator is connected to the high voltage output of the TREK and to the ground. Both PC are synchronized.

![Test setup](image)

**Fig. 4-8: Test setup.**

![Main features](image)

**Fig. 4-9: Main features of the high-voltage amplifier TREK Model 5/80 [33, 43].**

### 4.4 Test Procedure

The test procedure is summarized in Fig. 4-10. After the positioning of the cruciform functional model in the biaxial loading device, the biaxial strains measurement is started (see section 8.1.2 step 9). The maximal biaxial loads (for instance 1.5 [kg]) are applied to the cruciform specimen. After releasing the brakes both in x- and y-direction, a relaxation period of about 2.5 [min]
must last before the electrical activation of the DE-actuator. This time period allows the active envelope to achieve a quasi-static equilibrium state. The voltage cycle is shown in Fig. 4-11. The electrical activation lasts 6 [s]. Since the data acquisition frequency of the video extensometer is quite low (10 [Hz]), the activation cycle begins and ends with a ramp (0 [kV] - 3.5 [kV] and 3.5 [kV] - 0 [kV]), which allows the continuous tracking of all four white reference dots. Then, the brakes in x-direction are blocked, and the weights reduced, while those in y-direction are kept constant. At this point the previous procedure can be repeated. After performing the test with the minimal loads (about 1 [N]), both brakes in x- and y-direction are blocked. The load in x-direction is set to the maximum (1.5 [kg]), while that in y-direction is reduced. After releasing the brakes in both directions the test procedure continues, till the minimal loads in both longitudinal and transversal directions are reached.

![Diagram](image_url)

Fig. 4-10: Test procedure.

The test lasts about 3 hours. The electrical activation times have to be annotated in a protocol file (see documentation CD: “Test Protocol.xls”). It will allow to a visual basic based program (see Documentation CD: “DATA Evaluation.xls”) to identify the real activation times and the corresponding biaxial strains saved in the file generated by the video-extensometer PC.
4.5 Adhesiveness and Chemical Compatibility Test

The adhesiveness test setup is shown in Fig. 4-12. The adhesive contact area between the PU-layer (environmental/weathering protection layer of the NONEX) and the VHB4910 amounts to 21.6 [$cm^2$] and the maximal applicable load is 29.3 [$N$]. The equivalent maximal shear stress is $\tau_{\text{max}} = 13.5 [kPa]$. Moreover no chemical degradation occurred between the blimp envelope and the VHB4910 dielectric film during a two months long test. Alteration of the helium permeability of the envelope wasn’t investigated.
5 Results

In this chapter the most representative experimental results are reported.

Since the reliability of the manufacturing process is quite poor, only three different actuators were successfully characterized. Two actuators are non-symmetrically over-stretched \((\lambda_x, \lambda_y) = (7, 2.5)\) and \((\lambda_x, \lambda_y) = (6.5, 3)\)) and one symmetrically \((\lambda_x, \lambda_y) = (4.5, 4.5)\)). The largest activation strains \(\varepsilon_x(U)\) in longitudinal direction between the prestretched state and the activated one are listed in Tab. 5-1 as a function of the resulting bidirectional forces and the corresponding forces per unit length. The line loads are related to the electrode length at non-activated equilibrium.

\[
N_x = \frac{F_x}{L_{y,\text{ELECTRODE}}} \quad \text{(40)}
\]

\[
N_y = \frac{F_y}{L_{x,\text{ELECTRODE}}} \quad \text{(41)}
\]

\begin{tabular}{ll}
\text{L}_{x,\text{ELECTRODE}} \quad [m] & \text{Actual electrode length in x-direction (longitudinal blimp direction)} \\
\text{L}_{y,\text{ELECTRODE}} \quad [m] & \text{Actual electrode length in y-direction (transversal blimp direction)} \\
\end{tabular}

In other words, the line loads correspond to the ideal case, where the DE-actuator is completely coated on both sides of the dielectric film \((A_{\text{Active}}/A_{\text{Total}} \rightarrow 1)\). The adhesive area (the uncoated surface of the inferior actuator side) is not considered. In Tab. 5-1 the cases in red provide good activation strains and at the same time have a line load ratio \(N_y/N_x \subset [1, 2]\). Event though in three cases the line load ratio \(N_y/N_x\) exceeds the value of 2, they are considered as acceptable (this decision will be justified in the next section of this chapter).
The largest strain is achieved by an active envelope with the (6.5, 3)-over-stretched DE-actuator and amount to about 14.7 [%]. Unfortunately the required longitudinal strain at the blimp envelope location with same line load ratio $N_y/N_x = N_\theta/N_\phi = 1.18$ amounts only to about 4.9 [%]. The second largest strain is equal to 13.41 [%] with a line load ratio $N_y/N_x = 2.37$. The (7, 2.5)-over-stretched DE-actuator reaches the maximal longitudinal strains practically by the same line load ratios of the (6.5, 3). The symmetrically over-stretched DE-actuator obtained the lowest activation strains.

### 5.1 7 x 2.5

Fig. 5-1 shows the force displacement diagrams in both longitudinal ($x$) and transversal ($y$) directions for the active envelope specimen with a (7, 2.5)-over-stretched DE-actuator. The transversal load $F_y$ is constant in both diagrams (Fig. 5-1 left and right) and amounts to 2.86 [N]. The blue line and the red line of Fig. 5-1 left represent states of non-activated and activated equilibrium respectively. The displacement in millimeters is substituted by the dimensionless stretching ratio. For longitudinal loads above 6 [N] the active envelope keeps its fully elongated state in longitudinal blimp direction (Fig. 5-1 left). Below this limit the active envelope begins to passively wrinkle in $x$-direction, while it keeps the fully elongated state in $y$-direction (Fig. 5-1 right). The maximal activation strain $\varepsilon_x(U) = 10.89$ [%] is achieved for a biaxial load condition $(F_x, F_y) = (2.86$ [N], 2.86 [N]) and for an equivalent line load ratio $N_y/N_x = 1.19$ (see Tab. 5-1 and Fig. 5-1 left). As specified in section 4.1 the activation voltage is $U = 3.5$ [kV]. For all considered biaxial load states the activation strain $\varepsilon_x(U)$ in transversal blimp direction amounts practically to zero (Fig. 5-1 right). Since the strain in $y$-direction is blocked, the compression of the incompressible dielectric film due to the electrical activation can be compensated exclusively by a film elongation in $x$-direction. Thus, the elongation in longitudinal blimp direction results maximized.

<table>
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<tr>
<th>$\lambda_x$</th>
<th>$\lambda_y$</th>
<th>$\varepsilon_x(U)$</th>
<th>$\varepsilon_y(U)$</th>
<th>$F_x$</th>
<th>$F_y$</th>
<th>$F_x/F_y$</th>
<th>$N_x$</th>
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<td>0.14 [%]</td>
<td>2.86</td>
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<td>0.66</td>
<td>16.03</td>
<td>12.54</td>
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<td></td>
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<td>10.04 % [0.05 %]</td>
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<td>8.60 % [0.11 %]</td>
<td>2.86</td>
<td>5.81</td>
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<td>6.5</td>
<td>3</td>
<td>14.68 % [-0.08 %]</td>
<td>14.16 % [-0.05 %]</td>
<td>1.88</td>
<td>2.86</td>
<td>1.52</td>
<td>10.50</td>
<td>18.70</td>
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<td></td>
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<td>13.83 % [-0.01 %]</td>
<td>13.41 % [0.09 %]</td>
<td>1.39</td>
<td>2.86</td>
<td>2.06</td>
<td>7.78</td>
<td>20.28</td>
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</table>

Tab. 5-1: Best performances.
Fig. 5-1: Force-displacement diagrams $F_y = 2.86 \, [N]$; (left) longitudinal displacement; (right) transversal displacement.

Fig. 5-2 illustrates the force-displacement diagram for an active envelope with the same DE-actuator but for an increased load in $y$-direction ($F_y = 5.81 \, [N]$). The maximal activation strain $\varepsilon_x(U)$ is equal to 9.3 [%] and is achieved for a line load ratio $N_y/N_x = 2.35$ (see Tab. 5-1 and Fig. 5-2 left), which exceeds the maximal value typical of the ellipsoidal blimp body.

Fig. 5-2: Force-displacement diagrams $F_y = 5.81 \, [N]$; (left) longitudinal displacement; (right) transversal displacement.

The activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) directions as a function of the resulting biaxial forces is shown in Fig. 5-3. The diagram summarizes the results of the entire experimental characterization.

The activation strain in $y$-direction (yellow dots) is practically equal to zero for all biaxial loads. Only a strong reduction of $F_y$ allows to the active envelope to wrinkle and consequently to elongate under the action of an electrical activation ($\varepsilon_{y,\text{MAX}}(U) = 2 \, [%]$). Noteworthy is the fact that the progressive reduction of the force in transversal direction $F_y$ causes the increment of the maximal activation strain $\varepsilon_x(U)$ in longitudinal blimp
direction. In other words, high loads in $y$-direction impede the elongation in $x$-direction. The reduction of the transversal load not only consents to increase the longitudinal activation strain $\varepsilon_x(U) = 9.3\%$, but also to decrease the line load ratio from $N_y/N_x = 2.35$ to $N_y/N_x = 2$. Thus, the typical line load ratio of the blimp can be respected.

As highlighted in Fig. 5-3 the reduction of $F_x$ below the value of about 6 [N] allows to the non-activated active envelope to partially relax. The activation strain not only can compensate this envelope contraction, but it is blocked by the blimp envelope after reaching its fully elongated state (see also Fig. 3-4 2c-3c). The ideal activation strain $\varepsilon_x(U)$ corresponds to the case, where the partial relaxation is fully compensated through the electrical activation (see Fig. 3-4 2b-3b). A further reduction of $F_x$ leads to pre-stretching film conditions that don’t allow anymore to get the fully-elongated state of the blimp envelope through the electrical activation (see Fig. 3-4 2a-3a).

Fig. 5-4 shows the activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) blimp direction as a function of the resulting line loads related to the electrode length at non-activated equilibrium state. The considerations expressed for the previous diagram are still valid. The differences are due to the fact that the line loads in $x$- and $y$ direction are not linearly correlated (see Fig. 5-5).
Fig. 5-4: Activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the line loads at non-activated equilibrium.

Fig. 5-5: Transversal line load ($N_y$) as a function of the longitudinal one ($N_x$).

5.2 6.5 x 3

Fig. 5-6 shows the force displacement diagrams in both longitudinal ($x$) and transversal ($y$) directions for the active envelope specimen with a (6.5, 3)-over-stretched DE-actuator. The transversal load $F_y$ is constant and amounts to 1.88 [N]. The maximal longitudinal activation strain $\varepsilon_x(U) = 14.68$ [%] is reached for a biaxial load condition ($F_x$, $F_y$) = (1.88 [N], 1.88 [N]) and an
equivalent line load ratio $N_y/N_x = 1.18$ (see Tab. 5-1 and Fig. 5-6 left).
Noteworthy is the fact that the maximal longitudinal elongation $\varepsilon_x(U)$ is achieved without reaching the fully-elongated state of the blimp envelope. Thus, an activation with an higher voltage ($U \approx 4 \,[kV]$) would lead to a larger activation strain ($\varepsilon_x(U) = 19 \,\%$). A small partial relaxation of the active envelope in transversal direction occurs when $F_x$ is decreased (Fig. 5-6 right). Furthermore the partial relaxation is not compensated through the electrical activation ($\varepsilon_y(U) = 0 \,\%$).

Fig. 5-6: Force-displacement diagrams $F_y = 1.88 \,[N]$; (left) longitudinal displacement; (right) transversal displacement.

Fig. 5-7 shows the force displacement diagrams in both longitudinal ($x$) and transversal ($y$) directions for a constant load $F_y = 3.85 \,[N]$. The maximal activation strain $\varepsilon_x(U) = 13.41 \,\%$ is reached for a biaxial load $(F_x, F_y) = (1.88 \,[N], 3.85\,[N])$ and an equivalent line load ratio $N_y/N_x = 2.37$ (see Tab. 5-1 and Fig. 5-7 left). Also in this case, an higher activation voltage ($U \approx 3.8 \,[kV]$) could lead to higher activation strains ($\varepsilon_x(U) = 16 \,\%$). No activation strain in transversal direction is registered (Fig. 5-7 right).

Fig. 5-7: Force-displacement diagrams $F_y = 3.85 \,[N]$; (left) longitudinal displacement; (right) transversal displacement.
Fig. 5-8 shows the activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the resulting biaxial forces. Also in this case the decrease of the transversal load $F_y$ causes an augmentation of the maximal activation strain $\varepsilon_x(U)$, but for values below 1.88 [N] it starts to diminish.

Fig. 5-8: Activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the biaxial forces.

Fig. 5-9 illustrates the activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the resulting line loads related to the electrode length at non-activated equilibrium state.

Fig. 5-9: Activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the line loads at non-activated equilibrium.
5.3 4.5 x 4.5

Fig. 5-10 shows the force displacement diagrams in both longitudinal ($x$) and transversal ($y$) directions for the active envelope specimen with a (4.5, 4.5)-over-stretched DE-actuator. The transversal load $F_y$ is constant and amounts to $1.88 \, [N]$. The maximal longitudinal activation strain $\varepsilon_x(U) = 9.67 \, [%]$ is reached for a biaxial load condition $(F_x, F_y) = (0.90 \, [N], 1.88 \, [N])$ and an equivalent line load ratio $N_y/N_x = 2.28$ (see Tab. 5-1 and Fig. 5-10). Since the maximal longitudinal elongation is reached at the last load step $F_x$, larger strains $\varepsilon_x(U)$ are expected. The activation strain $\varepsilon_y(U)$ differs from zero for biaxial load states with $F_x > 6 \, [N]$.

![Fig. 5-10: Force-displacement diagram $F_y = 1.88 \, [N]$ for both longitudinal and transversal displacements.](image)

Fig. 5-11 shows the force displacement diagrams in both longitudinal ($x$) and transversal ($y$) directions for a constant transversal load $F_y = 2.86 \, [N]$. The maximal longitudinal activation strain $\varepsilon_x(U) = 7.98 \, [%]$ is reached for a biaxial load condition $(F_x, F_y) = (0.90 \, [N], 2.86 \, [N])$ and an equivalent line load ratio $N_y/N_x = 3.42$ (see Tab. 5-1 and Fig. 5-11). In contrast to the previous case, no activation strain in transversal direction ($\varepsilon_y(U)$) is registered. Thus, the previous odd phenomenon could be due to the fact that the biaxial loading device is unsuitable for the characterization of active envelope cruciform specimen with symmetrically over-stretched DE-actuator by low biaxial loads.
Fig. 5-11: Force-displacement diagram $F_y = 2.86 \, \text{[N]}$ for both longitudinal and transversal displacements.

Fig. 5-12 shows the activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) directions as a function of the resulting biaxial forces. The symmetrical distribution of the activations strains is due to the symmetrical over-stretching conditions of the dielectric film. The maximal activation strains are reached by the last load step.

Fig. 5-12: Activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the biaxial forces.

Fig. 5-13 illustrates the activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the resulting line loads.
related to the electrode length at non-activated equilibrium state. Also in this case the activation strains are symmetrically distributed.

![Activation strain ε(U) in longitudinal (red dots) and transversal (yellow dots) direction as a function of the line loads at non-activated equilibrium.](image)

Fig. 5-13: Activation strain $\varepsilon(U)$ in longitudinal (red dots) and transversal (yellow dots) direction as a function of the line loads at non-activated equilibrium.
6 Discussion and Conclusions

In this chapter some aspects highlighted by the experimental characterization of the functional models and the feasibility of the active envelope proposed in section 1.7 are discussed on the base of the experimental results. The quasi-static model for the description of the mechanical behavior of the active envelope introduced in section 3.1.2 based on a parallel connection between a spring and a rigid element was experimentally confirmed. Furthermore, a linearization of the results is possible. This would allow to reduce the loading steps needed for the experimental characterization of the active envelope functional model.

The theoretical modeling of the active envelope based on a hyperelastic film model of section 3.1.4 predicts that active envelopes with asymmetrically over-stretched DE-actuator provide low activation strains \( \varepsilon_x(U) \) and high longitudinal forces per unit length. On the other hand active envelopes with symmetrically over-stretched DE-actuator achieve large activation strains \( \varepsilon_x(U) \), but they exert low longitudinal line loads. This trend was experimentally confirmed. In fact, the highest longitudinal force per unit length is exerted by the active envelope with the (7, 2.5)-over-stretched DE-actuator, while the lowest values belongs to the active envelope with (4.5, 4.5)-over-stretched film. Furthermore, even though the active envelope with symmetrically over-stretched DE obtains the smallest elongations, Fig. 5-12 highlights that the maximum activation strain potential wasn’t completely reached. In fact, the proposed biaxial loading device is unsuitable for the characterization of the active envelopes with symmetrically over-stretched DE-actuator. The friction losses in the pulleys and the accentuated deflection of the specimen due to the low applied biaxial loads lead to measurement errors.

The line load values predicted by the model differ from the experimentally determined ones (compare Tab. 3-1 with Tab. 5-1). The theoretical model could be adapted to the experimental results through a suitable stiffness constant, defined as a function of the actual biaxial stretching conditions of the dielectric film.

The best longitudinal activation strain performance is achieved, when the activation strain in transversal direction \( \varepsilon_y(U) \) is blocked. In other words, the compression of the incompressible dielectric film during the electrical activation is transformed exclusively in an elongation in \( x \)-direction. This conclusion is contradicted in part by the phenomenon illustrated in Fig. 6-1. In fact, even though the activation strain in transversal direction is blocked, the wrinkling of the DE-actuator in this direction is not impeded. As the theoretical model doesn’t consider this particular phenomenon, some prediction errors have to be taken in account.
Fig. 6-1: Wrinkling of the DE-actuator \((\lambda_x, \lambda_y, \sigma_x, \sigma_y) = (6.5, 3); (F_x, F_y) = (1.88 [N], 3.85 [N])\) in transversal direction.

The largest longitudinal activation strain is achieved by the active envelope with a \((6.5, 3)\)-over-stretched DE-actuator. It amounts to \(\varepsilon_x(U = 3.5 [kV]) = 13.41 [%]\) and it is reached for a biaxial load \((F_x, F_y) = (1.88 [N], 3.85[N])\), which corresponds to an equivalent line load ratio \(N_y/N_x = 2.37\). Fig. 5-7 highlights the fact that through a higher electrical activation voltage \((U \cong 3.8 [kV])\) the fully-elongated state of the blimp envelope could be reached. The resulting activation strain \(\varepsilon_x(U) = 16 [%]\) satisfies the lateral strain requirement \(\varepsilon_y = 15.05 [%]\) for steady swimming defined in section 2.2 on the base of the rainbow trout motion. Furthermore, the reduction of the transversal load not only allows to increase the longitudinal activation strain \(\varepsilon_x(U) = 13.41 [%]\), but also to decrease the line load ratio from \(N_y/N_x = 2.37\) to \(N_y/N_x = 2\) (Fig. 5-8). Thus, the blimp membrane stress ratio can be fulfilled. The membrane stress requirement \(N_x(\Delta p = 300 [Pa]) = N_y(\Delta p = 300 [Pa]) = 80 [N/m]\) defined in section 2.1.2 for a 6 meters long and 1 meter wide ellipsoidal blimp can be fulfilled through the stacking of eight DE-actuators (see Tab. 5-1: 10.48 [N/m] \(\times 8 = 83.84 [N/m]\)). Unfortunately, the low data acquisition frequency of the employed video-extensometer didn’t allow the investigation of the strain rate requirements. Nevertheless, the theoretical results obtained through a model for the characterization of the dynamical behavior of DE-circle actuators (see section 3.2) are very promising. The experimental results allow to conclude that the proposed solution for an active envelope is feasible at least for steady swimming.
7 Outlook

The activation strain potential of the active envelopes with asymmetrically over-stretched DE-actuator was completely and successfully characterized through the proposed biaxial loading device. Unfortunately, it is unsuitable for the characterization of the active envelopes with symmetrically over-stretched DE-actuator. In fact, the friction losses in the pulleys and the accentuated deflection of the specimen due to the low applied biaxial loads lead to measurement errors. By increasing the planar dimensions of the attached DE-actuator or by stacking several film layers, the resulting forces needed to keep the dielectric film stretched would result augmented. Thus, this measure could reduce the deflection of the specimen and at the same time the influence of the friction losses.

The experimentally obtained results don’t have a statistical validity. Thus, further experimental characterizations are required in order to improve the understanding of the non-activated and activated mechanical behavior of the active envelope. In particular functional models with multi-layered DE-actuators, different dielectric materials (VHB4905, post-processed VHB4910) and higher activation voltages have to be characterized.

Furthermore, the investigation of the strain rates requirements through a video extensometer with higher sampling frequency must be carried out. In alternative to the video-extensometer, the biaxial strains measurement could be performed through the more reliable digital image correlation technique (DIC). Furthermore, by employing two cameras the out of plane displacement due to the deflection of the specimen could be quantified and the biaxial strains corrected.

A possible alternative to the proposed solution for an active envelope is the attachment of the over-stretched DE-actuator to an in longitudinal direction pre-wrinkled blimp membrane. In fact, the DE-actuator would be able to fully-elongate the pre-wrinkled envelope through the electrical activation already after the mounting procedure. Since the partial relaxation of the blimp envelope between over-stretched state and pre-stretched state wouldn’t be required, the line loads exerted by the over-stretched dielectric film would result higher. Thus, the number of the DE-actuator layers needed to fulfill the membrane stress requirement would decrease. Therefore, the reliability of the active envelope would result improved.

To overcome the difficulties related to the manual manufacturing of actuators with multiple layers, the longitudinal membrane stress requirement could be reduced by decreasing the internal pressure. For instance, the halving of the internal pressure leads to an halved longitudinal membrane stress requirement $N_x(\Delta p = 150 [Pa]) = 40 [N/m]$, which can be fulfilled through the stacking of four (6.5, 3)-over-stretched DE-actuators.
An additional issue is the perforation of the blimp envelope caused by the electrical breakdown of the DE-actuator (Fig. 7-1). This problem could be avoided by separating the actuator by the blimp envelope by means of a protective layer, or by limiting the current in case of short circuit.

Fig. 7-1: Perforation of the blimp envelope caused by the electrical breakdown of the DE-actuator.
8 Appendix

8.1 Manufacturing Process

The employed materials, tools, components and devices are:

1 Bi-adhesive VHB4910 film from 3M [40]: it plays the role of dielectric elastomer for the compliant capacitor (Fig. 8-1 1).

2 Bi-adhesive VHB4905 film from 3M [40]: it is used as reinforcement for the electrical contacts.

3 Ketjenblack Silicon Coating Mixture: the coating of the VHB4910 is realized thanks to a mixture consisting of carbon particles (Ketjenblack EC-300J) and silicone (Fig. 8-1 2).

Coating Mixture for 3 DE-actuators: (1) Mix 2 [g] of Ketjenblack EC 300J with 60 [g] of toluol; (2) Mix 15 [g] of silicon with 6 [g] of cross-linking hardener in a separate bin; (3) Mix 18 [g] of the silicon-cross linking hardener mixture with the Ketjenblack-toluol mixture.

4 Conductive tape: the electric conductive tape makes the application of the voltage to the coated surfaces possible (Fig. 8-1 3).

5 Electrical wire: it connects the electrode to the high voltage source or to the ground (Fig. 8-1 4).

6 Reference dots: they allow to the video extensometer the measurement of the biaxial strains (Fig. 8-1 5).

7 Rope: four PA-ropes are responsible for the load transmission from the balance pan to the cruciform arm fastening (Fig. 8-1 6).

8 Cold spray, roller knife, roller brush: they are employed for the separation of the DE-actuator from its support frame (Fig. 8-1 7).

9 Blimp envelope: the NONEX Al+ 925 membrane is used as blimp envelope (Fig. 8-1 8).

10 PVC plate: the PVC plate supports the blimp envelope during the mounting of the DE-actuator on the blimp envelope (Fig. 8-1 9).

11 Active envelope support frames: these two frames allow to keep the blimp envelope tight during the attachment of the DE-actuator (Fig. 8-1 10).
12 **EAP support frame:** on this frame a portion of over-stretched film can be stuck, and separated from the stretching machine (Fig. 8-1 11).

13 **Protective Prena layer:** it allows to separate the DE-actuator from its frame by means of a roller knife without damaging the blimp envelope (Fig. 8-1 12).

14 **Dot positioning mask:** it allows the positioning of the white reference dots for the video extensometer (Fig. 8-1 13).

15 **Spacer blocks:** they facilitate the centering of the DE-actuator on the blimp envelope (Fig. 8-1 14).

16 **Balance pan:** a balance pan is fixed at the end of each rope. It allows the application of weights (Fig. 8-1 15).

17 **Cruciform pattern:** it allows the cut of a cruciform envelope specimen (Fig. 8-1 16).

18 **Fastening:** the four PVC fastening elements allow the load transmission to the cruciform functional model arms (Fig. 8-1 17).

19 **Video extensometer PC and LabVIEW PC:** the first one is responsible for the measurement of the biaxial strains. The second one allows the application of the desired voltage cycle through a LabVIEW based program (AWC.vi) (Fig. 8-1 18).

20 **Video extensometer camera:** it provides the PAL video signal for the video extensometer PC (Fig. 8-1 19).

21 **Camera stand:** it keeps the video extensometer camera centered over the DE-actuator (Fig. 8-1 20).

22 **Biaxial loading device:** the biaxial loading device consists of four pulleys and four supports with hand lever for the active envelope support frames (Fig. 8-1 21).

23 **Pre-stretching machine:** this machine is able to stretch the dielectric film in planar directions. After stretching the film, the support frames can be positioned under it thanks to two guide rails. Afterwards the film can be stuck on the frames (Fig. 8-1 22).

24 **High voltage amplifier (TREK):** it provides the high voltage signal for the activation of the DE-actuator (Fig. 8-1 23).

25 **LabVIEW acquisition card:** the board NI 6030E from National Instruments is used as data acquisition hardware. It provides the input signal for the high voltage amplifier (Fig. 8-1 24).
8.1.1 Manufacturing of the DE-Actuator

Step 1: Manufacturing of the electrical contacts

The electrical contacts consist of an electrical wire and a piece of conductive tape. The manufacturing is shown in Fig. 8-2. The larger contact will connect the inferior electrode (electrode facing the blimp envelope), while the small one will connect the superior electrode. The dimensions of the conductive tape for both electrical contact types are illustrated in Fig. 8-3.
Step 2: Sticking of the VHB4910 film on the DE-actuator support frame

This machine shown in Fig. 8-4 a is able to stretch the dielectric film in planar directions. After stretching the film, the support frames can be positioned under it thanks to two guide rails. Afterwards the film can be stuck on the frames. In order to remove the frames from the stretching machine, the film around the frames sides must be cut with a suitable roller knife. Then, a support frame with a portion of over-stretched film is be positioned on a table. The dielectric film and the table surface are separated thanks to a cookie sheet (Fig. 8-4 b).
Step 3: Coating of the superior side of the DE-film

In order to achieve a good electrode, four covering strips are positioned on the film surface that will not be coated (Fig. 8-5 a). The covering strips can be easily positioned thanks to markers located on the support frame. The coating mixture is applied through a suitable brush (Fig. 8-5 b). The coating surface must be homogeneous. If it is necessary, an additional layer of coating mixture can be applied. The superior electrode geometry is specified in Fig. 8-9.

![Fig. 8-5: Coating of the superior electrode: (a) positioning of the covering strips; (b) coating of the film.]

Step 4: Application of the electrical contacts to the superior electrode

After removing carefully the covering strips, an electrical contact is applied on two corners of the superior electrode by keeping a distance of about 1.5 [cm] (Fig. 8-6 a). Then, the electrode is connected to the electrical contact through a coating mixture strip (Fig. 8-6 b). The DE-actuator support frame can be now turned on the other side.

![Fig. 8-6: (a) Positioning of an electrical contact in a corner of the superior electrode; (b) connection of the electrical contact with the superior electrode through a coating mixture strip.]

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Step 5: Coating of the inferior side of the DE-film

Four covering strips are positioned by keeping a distance of about 3 \[mm\] from the sides of the superior electrode (Fig. 8-7 a and Fig. 8-9). After the coating of the inferior electrode (electrode that will be in direct contact with the blimp envelope) and the removal of the covering strips, two electrical contacts can be positioned as shown in Fig. 8-7 b and Fig. 8-9.

The final result is illustrated in Fig. 8-8. The drying of the coating mixture lasts about 12 hours. Before proceeding with the mounting of the DE-actuator on the blimp envelope, the conductive strips between electrical contacts and electrodes have to be coated again with a further layer of Ketjenblack silicone mixture.

The electrode geometry proposed in Fig. 8-9 guarantees a good reliability of the actuator. In fact the electrical contacts are far away from the zone subjected to electrostatic stress. Furthermore, the superior electrode is smaller than the inferior one. This measure allows to reduce the mechanical and electrostatic stresses along the electrode sides.
8.1.2 Manufacturing of the Active Envelope

Step 1: Cutting of the blimp envelope

A portion of envelope material (NONEX) is cut thanks to a roller knife and a cruciform pattern (Fig. 8-10 a). Then, the cruciform envelope is attached to the cruciform pattern through bi-adhesive tape pieces.
Fig. 8-10: Cutting of the blimp envelope: (a) positioning of the cruciform pattern and cutting of the envelope (b) fixation of the cruciform envelope to the cruciform pattern through bi-adhesive tape pieces.

Step 2: Application of the fastening elements

A bi-adhesive strip is applied to the four PVC-fastenings (Fig. 8-11 a). Then, the four fastening can be attached to the cruciform envelope arm ends (Fig. 8-11 b).

Fig. 8-11: (a) Application of a bi-adhesive tape stripe on a fastening element; (b) fixation of the fastening element on a cruciform envelope arm.

Step 3: Fixation of the blimp envelope

After removing the cruciform envelope from the cruciform pattern, it will be fixed between two support frames (Fig. 8-12 a). Afterwards, the two frames are positioned on a PVC plate, which will support the envelope during the attachment of the DE-actuator. Then, four spacer blocks and a protective layer consisting of Prena are arranged as shown in Fig. 8-12 b. The spacer blocks allow to center easily the DE-actuator on the cruciform envelope. The Prena layer allows to separate the DE-actuator from its frame by means of a roller knife without damaging the blimp envelope.
Fig. 8-12: (a) The cruciform segment is kept tight by two frames; (b) positioning of the envelope support frames on the PVC tablet and arrangement of the protective Prena layer and of the spacer blocks.

**Step 4: Reinforcement of the electrical contacts**

The electrical contacts are reinforced with a piece of bi-adhesive VHB4905 (Fig. 8-13 a and b). This prevents from tearing accidentally the electrical contacts, and facilitates the cutting of the dielectric film (see step 6).

Fig. 8-13: Reinforcement of the electrical contacts: (a) inferior contact; (b) superior contact.

**Step 5: Mounting of the DE-actuator on the blimp envelope**

The support frame with the DE-actuator is centered on the cruciform envelope as shown in Fig. 8-14 a. Afterwards, the dot positioning mask is located on the superior electrode (Fig. 8-14 b). Then, four reference dots are inserted in the four holes of the mask. Thanks to a roller brush the dielectric film is attached to the blimp envelope by exerting a light pressure on it.
Step 6: Separation of the DE-Actuator from the support frame

The DE-actuator is separated from its support frame thanks to a roller knife (Fig. 8-15 b). Before proceeding with the cut of the dielectric film, it is embrittled through a cold spray (Fig. 8-15 a). In order to avoid the damaging of the envelope, the cut of the film must take place in correspondence of the Prena layer.

Step 7: Further reinforcement of the electrical contacts

Before removing the Prena layer (Fig. 8-16 b), the superior electrical contacts have to be reinforced with a further VHB4905 piece (Fig. 8-16 a). This measure will guarantee a good adhesion between the Ketjenblack strip and the conductive tape. Furthermore, it will reduce the fire risk in case of disruptive discharges between the mixture strip and the conductive tape (the blimp envelope and the conductive tape are inflammable).
Step 8: Positioning of the active envelope in the biaxial loading device

The active envelope support frames are positioned in the biaxial loading device (Fig. 8-17 a) Afterwards, the maximal biaxial loads (for instance 1.5 [kg]) are applied to the cruciform specimen arms (Fig. 8-17 b). Before releasing the cruciform functional model, the calibration of the video extensometer has to be performed. The video extensometer program needs a reference distance between two points. Then, the biaxial measurement procedure is started (the start time has to be reported in the test protocol file: see Documentation CD: “Test Protocol.xls”).

Step 9: Starting of the test procedure

After starting the measurement procedure, the superior active envelope support frame must be removed carefully and rapidly (Fig. 8-18 a). Afterwards, the inferior support frame is removed (Fig. 8-18 b) and the electrical wires are connected to the high voltage source and to the ground respectively. Now the test procedure of section 4.4 can be started.
Fig. 8-18: (a) Removal of the superior active envelope support frame; (b) removal of the inferior active envelope support frame.
8.2 CAD-Drawing
8.3 *Heptax, Octax, Nonex*

**Heptax 525: 7 Layer - Transparent Barrier Material**

- **Composition:** PA // EVOH // PA // PE
- **Thickness:** 25 micron
- **Yield:** 38.1 m³/kg
- **Specific Weight:** 26.2 g/m²
- **Oxygen Transmission:** 6.9 cc/m²/24h at 20°C, 65%RH.
- **Helium Transmission:** 0.8 litres/m²/d at 20°C, 30% RH.
- **Haze:** 3.0 %
- **Tensile Strength:** Machine Direction 100 MPa
  - Transverse Direction 102 MPa
- **Elongation:** Machine Direction 153 %
  - Transverse Direction 90 %
- **Coefficient of Friction:** PE / PE 0.5 - 0.46
  - PA / PA 0.59 - 0.57

**Thermal Weld Properties:**

Rel. seam strength: Strength of the thermal weld in relation to the material strength.

All data given are based on tests provided by aerofabrix, the manufacturer or costumers. Values are typical, but given without any warranty.
Heptax 725: Measured Properties

![Graphs showing stress-strain relationship for Heptax samples in MD (Richtung 1) and TD (Richtung 2).](image)

According EN ISO 13954-1 at 20mm/min. (TU Munich)

- Secant Modulus:
  - MD: 2.36 GPa (DIN EN 2561)
  - TD: 1.89 GPa
- Tensile Strength:
  - MD: 50.1 MPa
  - TD: 66.4 MPa

Octax 825: 8 Layer – Dual Barrier Material

Mechanical Properties:

see Heptax 525.

- Metal Barrier Shield:
  - Average Thickness of Aluminum: 70 nm
  - Helium Transmission: 0.8 litres/m²/d at 20°C, 30% RH.
  - Optical Density: 2.8
  - Thermal Emissivity: < 0.05

Nonex 925: 9 Layer – High End Dual Barrier Material

- Scratch resistant metal barrier surface.
  - Additional 2K primer WP6/thickness: 0.3 μm.
  - Temperature resistance of the primer: 180 - 190°C
8.4 Figure List

Fig. 1-1: Airship categories: (a) non-rigid airship, the “Spirit of Innovation” of the Goodyear company fleet [35]; (b) semi-rigid airship, the Zeppelin NT [36]; (c) rigid airship, U.S. Navy Zeppelin ZRS-5 "USS Macon".

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