BIOMIMETIC AIRSHIP DRIVEN BY
DIELECTRIC ELASTOMER ACTUATORS

DISSERTATION
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by
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Abstract

If this era is ever named after a type of material, it may well become the era of smart materials. Compliant structures with integrated sensors and actuators reacting autonomously to changes in the environment via intelligent feedback control loops allow for entirely new solutions, e.g. in light-weight structures. A promising technology meeting the requirements for new actuator systems are the dielectric elastomers (DE). The simple working principle, inexpensive materials and unique features like the scalability, compliance, and light weight make this class of the electro-active polymers (EAP) attractive for many applications. The combination of large active deformations uni- or biaxially and the noiseless expansion, is unique among the available actuator technologies.

The present thesis is divided into three parts: The first part treats the subject of up-scaling planar membrane dielectric elastomer actuators. Designs for large-scale actuators were developed. The verification that the material scales after theory is provided from measurements on a planar agonist-antagonist test-rig. The strain and force difference at activation were predicted with existing material models and parameters and compared to the experimental results. The mechanical behaviour of the large-scale actuators can be predicted with classical non-linear continuum mechanics, considering viscoelasticity. Active deformation as well as blocking force scale with the dimensions of the actuator and with the number of layers respectively. Electrical properties, such as capacity and serial resistance of the electrodes were analysed and found to scale according to theory as well.

The specific material used as dielectric, VHB 4910, is well-known and characterized thoroughly. It has shown the largest active strain and the highest energy density of all the materials used so far in DE actuators. On the other hand it features several disadvantages, such as a high viscosity, and a limited range of temperature due to a high glass tran-
sition temperature. Therefore, in a second part of the thesis, two other materials, introduced more recently, were evaluated. The first material consists of pre-stretched VHB 4910 that is modified with an interpenetrating TMPTMA network, resulting in a composite material of two intermingled elastomers, one under tension and one under compression. The second material is a silicone with corrugated silver electrodes. The three materials were characterized under comparable testing conditions and their performance as actuators was evaluated in an isotonic activation test and on an agonist-antagonist hinge configuration.

In the third part, a proof-of-concept for the large-scale VHB 4910 actuators was done on a biomimetic airship with fish-like propulsion. The airship is propelled by the interaction of a wave motion pattern of the body and caudal fin, resulting in a Karman-type vortex street in the wake of the airship. Bending the helium-inflated body and a caudal fin is realized with large planar DE actuators in agonist-antagonist configurations. The focus of the design process was on the DE actuators as artificial muscles. In a first flight test, the transfer of the fish-like movement from water to air was verified. Valuable experimental experience was gathered concerning large-scale DE actuators, which can be used for future large-scale structures in active and adaptive systems.
Zusammenfassung


dererseits weist es mehrere Nachteile auf, wie z.B. eine hohe Viskoelas-
tizität und einen begrenzten Temperaturbereich, in dem es angewendet
werden kann. Aus diesem Grund wurden zwei andere Materialien unter-
sucht: Beim ersten Material wird vorgedehntes VHB 4910 nach einem, an
der UCLA entwickelten Verfahren, mit einem interpenetrierenden Poly-
mernetzwerk (IPN) aus TMPTMA versetzt. Dabei entsteht ein neues
Composite-Material aus zwei mikromechanisch miteinander vernetzten
Elastomeren. Das zweite Material ist ein, seit kurzem bei Polypower
käuflich erwerbbliches, EAP bestehend aus einem Silikon-Dielektrikum
mit korrugierten Silberelektroden. Alle drei Materialien (VHB 4910
original, VHB 4910 IPN-modifiziert, und korrugiertes Silikon) wurden
unter gleichen Bedingungen elektromechanisch charakterisiert und als
Ausgangsmaterial für grossflächige Aktoren evaluiert.
Eine Machbarkeitsstudie mit den grossflächigen Aktoren aus VHB 4910
wurde durchgeführt an einem fischähnlichen Luftschiff. Das Luftschiff
wird angetrieben indem der Helium-gefüllte Rumpf und eine Flosse von
DE Aktoren in einer agonist-antagonist Konfiguration wellenförmig be-
wegt werden. Im Zentrum dieses Entwicklungsprozesses standen die
DE-Aktoren als künstliche Muskeln. In ersten Flugversuchen wurde die
Übertragbarkeit des Biegedrehschlages vom Wasser in die Luft nachgewiesen.
Betreffend der weiteren Entwicklung von grossflächigen DE-Aktoren kon-
nnten wertvolle experimentelle Erfahrungen gesammelt werden, die in
zukünftigen adaptiven und aktiven grossflächigen Strukturen genutzt
werden können.
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List of symbols

\(A\) \hspace{1cm} \text{Area (undeformed)}

\(A_{pp}\) \hspace{1cm} \text{Peak-to-peak amplitude}

\(a\) \hspace{1cm} \text{Area of the deformed actuator}

\(C\) \hspace{1cm} \text{Capacity of the actuator}

\(c_T\) \hspace{1cm} \text{Coefficient of thrust}

\(D\) \hspace{1cm} \text{Distance between the hinge and the measuring point for the blocking force measurements}

\(d\) \hspace{1cm} \text{Thickness of the electrode}

\(E\) \hspace{1cm} \text{Electrical field}

\(E_{BD}\) \hspace{1cm} \text{Breakdown field}

\(F_i\) \hspace{1cm} \text{Force in the DE film in state i (i:active, passive), in x-direction}

\(\varepsilon\) \hspace{1cm} \text{Permittivity } (\varepsilon_0 \cdot \varepsilon_r)

\(\varepsilon_0\) \hspace{1cm} \text{Vacuum permittivity}

\(\varepsilon_r\) \hspace{1cm} \text{Relative permittivity of the DE film}

\(F_D\) \hspace{1cm} \text{Drag}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_T$</td>
<td>Thrust</td>
</tr>
<tr>
<td>$F_{meas}$</td>
<td>Measured force difference at activation in a hinge configuration</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$\Delta F$</td>
<td>Difference in the blocking force between the activated and the passive actuator</td>
</tr>
<tr>
<td>$H$</td>
<td>Height of the undeformed actuator (y-direction)</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of the deformed actuator (y-direction)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$\eta_H$</td>
<td>Hull efficiency</td>
</tr>
<tr>
<td>$I$</td>
<td>Electrical current</td>
</tr>
<tr>
<td>$i(t)$</td>
<td>Current as a function of time</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of the undeformed actuator (x-direction)</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of the deformed actuator (x-direction)</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>Difference in length between activated and contracted actuator on an active hinge structure</td>
</tr>
<tr>
<td>$\lambda_{ij}^i$</td>
<td>Stretching ratio of the DE film in the state i (ps: pre-stretched, a: activated, ops: over-prestretched, c: contracted), in the principal direction $j=x,y,z$</td>
</tr>
<tr>
<td>$M$</td>
<td>Blocking moment of the active hinge structure</td>
</tr>
<tr>
<td>$m$</td>
<td>Blocking moment of the active hinge structure divided by the height of the actuator</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of DE layers</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>Power input</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>Power output</td>
</tr>
<tr>
<td>$p_{eq}$</td>
<td>The electrostatic pressure equivalent to the apparent three-dimensional state of stress in the DE film</td>
</tr>
<tr>
<td>$p_{max}$</td>
<td>Maximum equivalent electrostatic pressure at break-down</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Deflection angle</td>
</tr>
<tr>
<td>$Q$</td>
<td>Charge</td>
</tr>
<tr>
<td>$R$</td>
<td>Resistance</td>
</tr>
<tr>
<td>$R_S$</td>
<td>Specific sheet resistance</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Resistivity</td>
</tr>
<tr>
<td>$\rho_{air}$</td>
<td>Density of air</td>
</tr>
<tr>
<td>$S$</td>
<td>Scaling factor in the planar dimensions of the actuator</td>
</tr>
<tr>
<td>$St$</td>
<td>Strouhal number</td>
</tr>
<tr>
<td>$s_j$</td>
<td>Strain in the DE film principal direction $j=x,y,z$</td>
</tr>
<tr>
<td>$\sigma_j$</td>
<td>Stress in the DE film in the principal direction $j=x,y,z$</td>
</tr>
<tr>
<td>$T$</td>
<td>Thickness of the undeformed actuator (z-direction)</td>
</tr>
<tr>
<td>$t$</td>
<td>Thickness of the deformed actuator (z-direction)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Time constant</td>
</tr>
</tbody>
</table>
\(u, u_0\) Relative velocity of the object to the surrounding fluid
\(u_T\) Velocity of the accelerated air behind the propeller
\(u_A\) Velocity of the medium just before entering the propeller
\(V\) Voltage
\(V_{BD}\) Breakdown voltage
\(W\) Width of active hinge structure
\(W_{(i)}\) Strain energy function. (i) being the corresponding model (Yeoh, Ogden, Mooney-Rivlin, Arruda-Boyce)
\(W_{in}\) Energy input
\(W_{out}\) Output work of the actuator
\(\Delta x\) Measured displacement due to activation
\(Y\) Young’s modulus
Chapter 1

Introduction

1.1 Smart materials and structures

Fully integrated structural systems enable new possibilities in a vast range of fields, such as for example aerospace, automotive, architecture, building technologies, robotics, and biomedical applications. The involved new technologies, including among others microelectromechanical systems (MEMS), compliant structures, structural health monitoring and self-repairing systems, vibration damping and environment control, require active (also ”adaptive”, ”functional” or ”smart”) materials and structures. The definition of these terms may vary slightly, but can generally be summarized as structures or systems that sense and/or react to external stimuli or changes in the environment in (near) real-time [1]. Sometimes it is distinguished between the merely sensory and adaptive characteristics, e.g. structures with integrated sensors and actuators, and the ”smart” structures with a feedback control loop, which allows for autonomous functioning of the system [2]. The technologies used in these systems can be classified by means of their stimulus and response (Table 1.1, adapted from [3–5]). Looking closer at the actuator technologies (mechanical response) that have evolved, the main representatives are piezoelectrics, shape memory alloys (SMA) or shape memory polymers (SMP), magnetostrictives, as well as electronic and ionic electroactive polymers (EAP) [6].
Table 1.1: Overview over transducers used in “smart” materials, adapted from [3–5].

<table>
<thead>
<tr>
<th>Response</th>
<th>Electrical</th>
<th>Magnetic</th>
<th>Optical</th>
<th>Thermal</th>
<th>Mechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ferroelectric</td>
<td>Paramagnetic</td>
<td>Electroluminescent</td>
<td>Electrocaloric</td>
<td>Piezoelectric</td>
</tr>
<tr>
<td></td>
<td>Diamagnetic</td>
<td>Magnetostrictive</td>
<td>Fibre-optic (electro-optic)</td>
<td>Electronic EAP</td>
<td>Electronic EAP</td>
</tr>
<tr>
<td></td>
<td>Magnetoelectric</td>
<td>Electrochromic</td>
<td>Electrocaloric</td>
<td>Magnetic EAP</td>
<td>Ionic EAP</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Magnetoresistance</td>
<td>Hall-effect</td>
<td>Magneto-optic</td>
<td>Magnetostrictive</td>
<td>MR fluids</td>
</tr>
<tr>
<td></td>
<td>Diamagnetic</td>
<td>Magnetostrictive</td>
<td>Magnetocaloric</td>
<td>Magnetic SMA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ferromagnetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Photovoltaic</td>
<td>Gyrotropic</td>
<td>Photochromic</td>
<td>Photostrictive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Phosphorescent/Fluorescent</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Photorefractive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermocouples</td>
<td>Magnetocaloric</td>
<td>Thermoluminescent</td>
<td>Shape memory alloys</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermistors</td>
<td></td>
<td>Thermochromic (liquid crystals)</td>
<td>Shape memory polymers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyroelectrics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td>Piezoelectric</td>
<td>Piezomagnetic</td>
<td>Mechanochromic</td>
<td>Auxetic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Piezoresistive</td>
<td>Magnetostrictive</td>
<td>Triboluminescent</td>
<td>Thixotropic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electronic EAP</td>
<td></td>
<td>Photoelastic</td>
<td>(shear-thinning)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dilatant</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(shear-thickening)</td>
<td></td>
</tr>
</tbody>
</table>
Each of these actuator technologies has specific advantages and disadvantages [2]. While piezoelectric actuators feature relatively large output forces and high response speed, the active strains are very limited. Moreover they are usually stiff and brittle. Shape memory alloys and -polymers show large active strains and stresses, which results in a high energy density. On the other hand these materials can only be activated at low frequencies, the temperature range is limited and the hysteresis is usually high. Ferromagnetic SMA have been developed more recently and can be used at higher driving frequencies. Magnetostrictives have the advantage that they are controlled with a magnetic field and are therefore non-contacting. High forces can be generated, but moderate strains only. They are also stiff and the necessary equipment to generate the magnetic field makes such systems heavy and large [2]. EAP are polymers that change in shape or volume when activated with an electrical field. Polymers in general feature many attractive properties, that metallic or ceramic materials cannot provide. They are lightweight, inexpensive, fracture tolerant and compliant [1]. Accordingly, these transducers display much larger displacements, but at the same time lower forces. While EAP react slower than piezoceramics and magnetostrictives, they have shorter reaction times than SMA or SMP. On the other hand the energy density of EAP is lower than of shape memory materials [2]. A thorough comparison of various actuator technologies in a case study can be found in [7]. Among the EAP, two groups can be distinguished, the ionic and the electronic [1]. An overview of the classification of EAPs is shown in Figure 1.1 [8]. While ionic EAP show large displacements (often bending) at low voltages, they need to be in a wet environment, are not easily scalable and have short lifetimes. Electronic EAP on the other hand can be used in dry environment. They can be divided into several groups again, and this thesis concentrates on the dielectric elastomers (Fig. 1.1).

As actuators, dielectric elastomers are also called ’artificial muscles’, because their performance is closer to the biological muscles than most other technologies [1, 7]. In general it can be said that nature often serves as inspiration for smart systems, examples being e.g. the combined sensor-actuator functionality of the human eye that monitors the amount of light passing through the pupil or the adaptive wings of a bird [6]. The following Section will therefore briefly discuss the principle of biomimetics and specifically the fish-like propulsion from which this work sought inspiration.
1. Introduction

**Actively deforming polymers**

- Magnetically activated polymers
- Thermally activated polymers
- Electrically activated polymers (EAPs)
- Chemically activated polymers
- Light-activated polymers

**Ionic EAPs**

- Ionic polymer gels (IPGs)
- Ionomeric polymer-metal composites (IPMCs)
- Conductive polymers (CPs)
- Carbon nanotubes (CNTs)

**Electronic EAPs**

- Ferroelectric polymers
- Soft dielectric EAPs
  - Electrostrictive graft elastomers
  - Electrostrictive paper
  - Piezoelectric polymers (PVDFs)
  - Liquid crystal elastomers (LCEs)

Figure 1.1: The various classes of active polymers and how dielectric elastomers are classified [8], adapted from [1].

1.2 Biomimetics

The term 'bionics' was formed in 1960 to be “the science of systems whose functions are modelled on natural systems, or whose properties resemble those of natural systems, or are analogous to them.” [9]. The meaning of the term changed later and became associated with the use of electronically-operated artificial body parts and the original term was replaced with 'biomimetics'. To the first recorded examples from the 16th century belong the ideas of Leonardo da Vinci who drew technical solutions inspired by birds and Matthew Baker who built ships with shapes of fishes and thus reduced drag and improved manoeuvrability (Fig. 1.2) [10–12]. The idea of reducing drag by imitating the shape of a fish or bird for an airship was already documented in 1802 by Samuel Johann Pauly (Jean Pauly) [13].
1.2. Biomimetics

Fish-like propulsion

Mimicking the propulsion of fishes for technical devices has often been suggested in the last years [14–17], and is based on the investigations of anatomy, movement, and fluiddynamics of the living fish (e.g. [18, 19]). The impulse for the fish-like propulsion is generated from an active translation and rotation of a fin, generating an inverse Karman vortex street in the wake by accelerating the water (Fig. 1.3(a)). The generally known form of the Karman vortex street is in the wake of a body, such as e.g. a cylinder dragged through a fluid. The wake is then slower than the unperturbed water in front of the cylinder and we have a loss of impulse - drag is generated and energy is extracted from the fluid (an example is a fluttering flag) (Fig. 1.3(b)). The axial propulsion form of fishes, producing an inverse Karman vortex street in the wake, is designated by an undulation, proceeding through body and fin. This is the most common propulsion form, while other fishes use anal or dorsal fins or even paired fins such as the pectoral fins for their propulsion [20]. In 1926 Breder classified the fishes by the extent of body that is included in the propulsion into anguilliform, carangiform, and ostraciiform swimmers [18]. Figure 1.4 displays the anguilliform and three sub-groups of the carangiform swimming [21].

More recently, it was shown that the body generated vortices play a substantial role for the propulsion. In Figure 1.5, a schematic of the shedding of vortices during an entire cycle is shown [22]. Triantafyllou et al. [23] have distinguished two interaction modes between the body generated vortices and the oscillating caudal fin and tail-generated vortices: A high thrust can be generated by constructive pairing of body-generated and
1. Introduction

Figure 1.3: (a) Active undulation (creating thrust). (b) Passive undulation (creating drag) [19].

Figure 1.4: (a) Anguilliform (b) Carangiform (c) Subcarangiform and (d) Thunniform locomotion [21].

same-sign tail-generated vorticity. Body-generated vorticity paired with opposite-sign tail-generated vorticity on the other hand corresponds to a high efficiency.
1.2. Biomimetics

The advantage of these locomotion forms is that the propulsion is directly integrated and in series with the drag from the body, whereas in planes or airships the propellers are often in parallel to the drag. Hertel illustrated this with a simple example where he calculates the necessary power for a steady propulsion of a sieve with a propeller once in parallel and once in serial configuration [19]. Further explanations for the high efficiency of the fish-like propulsions are that the vortices rotate in the direction of swimming while in a propeller, a vortex is generated that rotates perpendicular to the direction of acceleration and the kinetic energy invested in that rotation is therefore lost entirely [24]. Fish and Lauder have made measurements with a series of small whales and compare their efficiency with that of a propeller [25]. Figure 1.6 shows that the whales perform slightly better, but mainly that they can adjust their movement and thus be efficient over a wide range of parameters, whereas the propeller is efficient only around a certain distinct operating point. Another great advantage is, that some fishes can turn with a radius of only 10 to 30 percent of their body length, while this requires

Figure 1.5: The vortex shedding of a straight swimming fish (full oscillation cycle) [22].
a significant deceleration of a ship and the turning radius will be in the order of a length of the ship [24].

![Graph showing efficiency of small whales compared to marine propeller](image)

**Figure 1.6:** Efficiency of small whales compared to the efficiency of a marine propeller. Adapted from [25].

Many projects have been inspired by the fish-like locomotion [14, 26–28]. A number of patents of fin driven boats or submarines are registered [29–31]. Scientific projects on fish robots include e.g. the RoboTuna (Massachusetts Institute of Technology) [14], the Robotic Fish (University of Essex) [26], the Tai-robot-kun (University of Kitakyushu) [27], and many more. Fish robots with unconventional actuators have been presented. Robots with pneumatic muscles were built [32]. A robot driven with piezoelectric actuators has been presented [33], shape memory alloys have been used [34, 35], and also conducting polymers and ionic polymer metal composites (IPMCs) have previously been suggested for the propulsion of fish robots [28, 36–38]. Dielectric elastomers have not been used for this kind of robot, and, working with very high voltages, may be difficult in water. Transferring the underwater locomotion to air on the other hand is theoretically possible and DE actuators are well suited for the activation of an inflated object.
1.3 Airships

Lighter-than-air technologies have long been pioneers in aviation. The first gas balloon was built in France in 1783 and the balloons had their first military applications and scientific missions around 1800. The classical airships were introduced around the turn of century 1899/1900 when the light-weight combustion engine was developed [39]. During the coming years, airships were used for long-distance transportation and for military purposes, e.g. surveillance and radar alert system. Even though airships were replaced almost completely by airplanes, which are less dependent of the weather and more efficient, the technology never quite disappeared from peoples heads and hearts. When Zeppelin ran out of money after the crash of the LZ4, this lead to the largest fund-raising campaign in Germany ever and still until now there are ongoing projects with airships. Examples for applications are heavy cargo transportation (e.g. SkyLifter [40]), tourism (e.g. Zeppelin NT, Airship ventures [41,42]), surveillance (e.g. LEMV [43]), research (e.g. Stratospheric platforms airships [44]), measuring systems or publicity (e.g. Goodyear Blimp [45]).

The classical airship is either rigid with an internal structure, without rigid structure (so called blimps) or semi-rigid, e.g. a blimp with a rigid keel. They are usually steered with fins with rudders and driven by propellers (Fig.1.7). These systems have a limited efficiency though. The size of the propellers diameters (propeller area $A$, Fig. 1.8) is restricted to avoid supersonic relative tip mach numbers. The thrust $F_T$ can be calculated with Equation 1.1.

$$F_T = \int (\rho_{air} u_T (u_T - u_0)) \delta A$$ (1.1)
Consequently, the air has to be accelerated quite significantly in order to generate enough momentum to compensate the drag due to body friction (high relative velocities between propeller air jet and surrounding air $u_T-u_0$, $\rho_{\text{air}}$ being the density of air), which reduces the efficiency. Additionally, because of the airflow around the hull, the advance flow velocity directly before the propeller $u_A$ is often different from the airship velocity. The so-called hull-efficiency can then be written as in Equation 1.2 and is therefore dependent of the ratio $u_0/u_A$ [47] (Fig.1.8). But while many methods for improving these technologies have taken place or are possible (stern propellers, optimization of propeller designs, low drag hull materials and shapes, etc.) the efficiency and manoeuvrability of this classical design is fundamentally limited.

$$\eta_H = \frac{F_D \cdot u_0}{F_T \cdot u_A}$$ (1.2)

![Figure 1.8: Scheme of an airship with the various flow velocities.](image)

The efficiency of propeller driven airships limited thus, the idea to adapt the efficient locomotion of animals on airships has inspired many projects. A variety of biomimetic model airships are shown in Figure 1.9 and include an airworm [48], a manta ray [49], jelly fishes [50], penguins [50] and an air fish [51]. Possible applications for these vehicles - apart from the publicity effect - include surveillance, animal observations or photography in places where noise may be a problem, such as e.g. concerts. The propellers of an airship produce a lot of noise which may be diminished with a biomimetic propulsion system. Another advantage of fish-like propulsion is the good manoeuvrability even at low speed, which is usually critical for airships.
1.4 Outline of this thesis

The goal of this thesis was to implement large planar dielectric elastomer actuators in an object, where their unique characteristics would show their full advantage. DE actuators are soft, light-weight membranes, which are easily scalable and they are ideal for the active deformation of inflated structures. The active material and the application of the loads can be distributed over a large area, which enables entirely new designs of smart systems. The muscles of fishes are distributed along their entire body and often all of it deforms and contributes to their propulsion [52]. Inspired by this, a biomimetic airship was built, where the fish-like propulsion is transferred into air and implemented with planar membrane DE actuators. The main objectives of this thesis include (a) the theoretical and experimental verification of up-scaling DE actuators, (b) the comparison of an acrylic dielectric elastomer to two newer
DE materials, and (c) the proof-of-concept of the applicability of large planar actuators on a biomimetic airship.

(a) New designs were developed for large-scale actuators. The up-scaling of the actuators was evaluated theoretically and experimentally. The actuators were thoroughly characterized in an agonist-antagonist (push-pull) configuration and the results compared to the theoretical predictions. Not only mechanical output parameters such as active strain and force difference were compared, but also electrical quantities, such as input power and serial resistance of the electrodes.

(b) The actuators made of the well-known and thoroughly characterized acrylic DE material VHB 4910 (see Section 2.2.1) feature several disadvantages. One of the most limiting is the large pre-stretch, which is necessary, and reduces lifetime and variety of designs. Two other materials that can be used at much lower pre-stretches were therefore characterized systematically and compared to VHB 4910. Actuators were built of all three materials and their performance compared. So far the modelling parameters of the newer materials had only been verified in lab-scale circular actuators of a few centimetres. Now the actuator performance was modelled for all materials and compared to the experimental outcome. The aim was to reach a more general conclusion of the influence of the material on the performance of the actuators.

(c) As a proof-of-concept, the large-scale membrane actuators were incorporated in the hull and on the tail-fin of a fish-like model airship. Just as on a real fish, or e.g. the natural muscles on a human arm, this is an agonist-antagonist configuration. While one actuator expands due to the activation, the opposite one contracts, due to the pre-stretch it was applied with. An undulating movement of body and fin can thus be provoked (Fig.1.10) and a fish-like propulsion of a lighter-than-air vehicle based on large planar DE actuators is achieved.
Figure 1.10: Agonist-Antagonist activation of fish-like airship.
Chapter 2

Dielectric elastomer transducers

In 1776 Volta explained an observation made by Fontana that volume changes occurred in the Leyden jar upon electrification. According to Carpi et al. he was the first to explain the physical principle underlying dielectric elastomer actuators [53]. According to Keplinger et al. [54], Röntgen first described the phenomenon of dielectric elastomer actuators on a caoutchouc stripe in 1880 [55]. He showed that an elastomer contracts in the thickness direction, and expands in length, when an electrical field is applied and thus converts electrical energy into mechanical work. The phenomenon was revisited in the 1990s when Pelrine and others started to investigate the potential for actuator applications more closely [56–58]. Very early a whole set of materials, designs, and applications, such as microrobotics, sound generators, and displays, was presented [56, 58]. But only after very large strains (> 100 %) were achieved with pre-stretched material [59] did the field really start to grow internationally and attracts an increasing interest until today.

In the past years, dielectric elastomers (DE) have become widely known as actuators, sensors, and for energy harvesting applications. In a first attempt, one can imagine a DE actuator as a compliant electrical capacitor: A elastomer membrane is coated on both sides with compliant electrodes. When an electrical voltage is applied between the electrodes (z-direction, Fig. 2.1), the opposite charges attract each other and the material contracts in the thickness direction. If the material is close to
incompressible, it will expand in plane (Fig. 2.1).

![Working principle of DE actuators.](image)

Figure 2.1: Working principle of DE actuators.

Various designs of active devices have been presented in the past years. We can distinguish between two general types, the contractile or stacked configuration and the expanding configuration. Stacked devices consist of many (often several hundreds or thousands) layers and the contraction in thickness is the required outcome. They are made from non-prestretched material and can transmit the electrostatic force directly onto an object. Expanding devices often work with a surrounding mechanical structure and mostly under some kind of pre-stretch, since a thin film cannot exert any force otherwise. Much work has been invested in improving the dielectric material, electrodes or both of them. As dielectric, so far, commercially available acrylics, silicones or polyurethanes have been used widely.

Potential applications cover a variety of fields, such as biomedical applications (e.g. limb prosthetics) [60,61], android or biomimetic robots [62], loudspeakers [58], tunable lenses and other optical devices [63], Braille devices [64,65], force feedback and tactile devices [66,67], pumps and valves [68], and many more.

### 2.1 Modelling

When an electrical field is applied across the thickness of a dielectric elastomer, the material in between contracts in the thickness direction, which leads to an expansion in plane if incompressibility of the material is assumed. After Pelrine et al. [69], the electro-mechanical coupling
can be calculated in a first attempt with the Maxwell stress, just as in a parallel plate capacitor. Since the capacitor is compliant, the equal charges to one side of the elastomer will at the same time repel each other and add to the expansion in plane \[63\]. The electrostatic pressure equivalent to the apparent three-dimensional state of stress is therefore twice the pressure of a parallel plate capacitor and can be described after Pelrine with Equation 2.1 [69].

\[
p_{eq} = \varepsilon_0 \cdot \varepsilon_r \cdot E^2 = \varepsilon_0 \cdot \varepsilon_r \cdot \left(\frac{V}{t}\right)^2
\]  

(\varepsilon_0 \text{ is the vacuum permittivity, } \varepsilon_r \text{ is the relative permittivity of the DE, } V \text{ is the electrical voltage that is applied, and } t \text{ is the resulting film thickness}). The use of this formula is derived from the Maxwell stress and can be used for incompressible, dielectrically isotropic membranes. Lately, the working principle has been analysed more precisely and a thermodynamic model of electrostriction has been developed by Suo et al. [70] (Eq. 2.3). A dielectric material contains charges which can move around to a certain degree. When an external field is applied, the dipoles will align and can bring the material thickness to increase or decrease. The Maxwell stress can account only for the decrease in thickness. While the former derivation was true only for ideal DE, which means specifically linear electric displacement and permittivity independent of the strain, now the model is derived such that it is valid for quasilinear dielectric behaviour (linear electric displacement but a permittivity that may vary with changes in strain [71]). It is now justified that the electrostrictive model may be used not only with small, but also with large deformations.

Several models also describe the actuator behaviour closer to electromechanical instability (pull-in) and shortly before electrical break-down [72–76]. An overview over the failure modes and the limitations of activation is given for spring-roll actuators (see Section 2.3) by Moscardo et al. in [77]. The area of allowable states for that case is limited by the strain at break in either direction, by a loss of tension in the material in either direction, by the electrical break-down strength, by the electromechanical instability, and for this particular design, by a plastic deformation of the spring in the core of the actuator (more generally, a failure of the rigid structure supporting the actuator).

From the electrostatic pressure, the active strain can be calculated with
Equation 2.2 [69], with $Y$ being the Young’s modulus.

$$s_z = -\frac{p_{eq}}{Y} = -\frac{\varepsilon_0 \cdot \varepsilon_r \cdot E^2}{Y} = -\frac{\varepsilon_0 \cdot \varepsilon_r \cdot (V/t)^2}{Y} \quad (2.2)$$

This assumption of a constant Young’s modulus (Hooke’s law) is however only valid for very small strains, since most of the dielectric membranes are not linear-elastic. The stress in the material is therefore related to the stretch in the material using the strain energy function $W_s$ [71,78,79] (Eq.2.3). The denotations for the measures and the stretching factors ($\lambda_i$) are shown in Figure 2.1. Often the relative permittivity $\varepsilon_r$ was assumed to be constant and the third term was omitted (with $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$).

$$\sigma_x - \sigma_z = \frac{\partial W_s}{\partial \lambda_x} \lambda_x - \varepsilon E^2 - \frac{1}{2} \frac{\partial \varepsilon}{\partial \lambda_x} E^2 \lambda_x \quad (2.3)$$

$$\sigma_y - \sigma_z = \frac{\partial W_s}{\partial \lambda_y} \lambda_y - \varepsilon E^2 - \frac{1}{2} \frac{\partial \varepsilon}{\partial \lambda_y} E^2 \lambda_y \quad (2.4)$$

Several hyperelastic models have been used, namely Yeoh (Eq.2.5), Ogden (Eq.2.6), Mooney-Rivlin (Eq.2.7), and Arruda-Boyce (Eq.2.8) models and the material parameters ($C_i, \mu_i, \alpha_i, A, N$) have been fitted to various materials [80–82].

$$W_{Yeoh} = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \quad (2.5)$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

$$W_{Ogden} = \sum \frac{2 \cdot \mu_i}{\alpha_i^2} \cdot (\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \quad (2.6)$$

$$W_{Mooney-Rivlin} = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \quad (2.7)$$

$$I_2 = \lambda_1^{-2} + \lambda_2^{-2} + \lambda_3^{-2}$$

$$W_{Arruda-Boyce} = A \cdot \left[\frac{1}{2}(I_1 - 3) + \frac{1}{20N}(I_1^2 - 9) + \frac{1}{1050N^2}(I_1^3 - 27) + \frac{1}{7000N^3}(I_1^4 - 81) + \frac{1}{673750N^4}(I_1^5 - 243)\right] \quad (2.8)$$
Occasionally, finite element modelling was employed to model actuators [80,82,83]. The challenge here is that shell elements (usually employed for this kind of complex shell structure) cannot deform in the thickness usually. Thermal expansion was sometimes used as a replacement, and in some cases the electromechanical coupling was implemented in an individual subroutine.

Time dependency has been considered fitting short- and long-term parameters. The time-dependent behaviour \( (C_{ij}^R) \) was modelled by multiplying the instantaneous hyperelastic material parameters \( (C_{ij}^0) \) with a time function \( g(t) \) (Eq. 2.9).

\[
C_{ij}^R = C_{ij}^0 \cdot g(t)
\]  

(2.9)

As time function, the Prony series (Eq. 2.10) [79] or a Kelvin-Voigt model (Eq. 2.11) [84] were used.

\[
g(t) = 1 - \sum_{k=1}^{n} (g_k \cdot (1 - exp(-\frac{t}{t_k}))
\]  

(2.10)

\[
g(t) = \varepsilon_0 + (\varepsilon_0 - \varepsilon_\infty) \cdot exp(-\frac{t}{\tau_R})
\]  

(2.11)

A more thorough description of the theory can be found e.g. in [70,85].

### 2.2 Material

#### 2.2.1 Dielectric membrane

The specifications for a dielectric membrane for the application as DE actuator include a low stiffness, high relative permittivity, and high electrical break-down strength. The film must be thin, incompressible and a good electrical isolator. When a certain electrical voltage is applied the elastomer contracts and its thickness is reduced. Through this, the electrical field is increased and the thickness may thus be reduced drastically very fast and instability may occur. To avoid this pull-in effect, a stiffening at large displacements is favourable (another possibility is e.g. to have a charge controlled system). Figure 2.2 shows a typical force-displacement behaviour for a hyperelastic material and an example for the activation behaviour. In an early screening study by Pelrine et al. [69]
Polyurethane, Silicone, Fluorsilicone, Ethylene propylene, Polybutadiene and Isoprene were identified as potentially interesting materials as dielectric. Three main groups of suitable materials emerged: silicones, polyurethanes, and acrylics \cite{59}. Each group has specific advantages that make them interesting for the application in DE transducers. Silicones are often very soft, they feature a low viscosity, and they can be operated in a large temperature range. Polyurethanes have a higher relative permittivity and larger force output than silicones. Acrylics feature a good dielectric strength. Among the acrylics, specifically VHB (a commercially available Very High Bond tape by 3M) showed the most promising performance in terms of actuation strain with active area strains up to 380\% \cite{86}. These results can only be reached with large pre-stretch of the material and therefore many investigations have been carried out on the correlation between pre-stretch and performance \cite{72,74,87,88}. It was found that the pre-stretch enhances the dielectric strength and it provides mechanical stability at expansion (no wrinkling or buckling). Additionally it decreases the thickness of the film, so that a lower activation voltage is needed for the same electrical field. More details to specific materials can be found in literature, e.g. \cite{89}.

![Graph](image.png)

**Figure 2.2:** Schematic of a typical hyperelastic material. The lower curve designates the fully activated characteristic. The area between the two curves contains the states that can be reached by activation.

All of these materials were not specifically designed for the use in DE transducers and much research has been conducted as to how to im-
prove the dielectric material with regard to this application. Most of it is aimed at increasing the relative permittivity, such that the activation voltage could be lowered, for safety reasons, but also for cutting the costs of supply and control electronics. Other modifications are targeted on softening the materials, reducing viscosity, and reducing the necessary external pre-stretch. A promising approach for lowering the stiffness has been shown lately with a thermoplastic polymer: Shankar et al. reported up to 245 % area strain with pre-stretched SEBS (nanostructured poly[styrene-b-(ethylene-co-butylene)-b-styrene] triblock copolymer, swollen with a mineral oil) [90]. A common approach to increase permittivity is to dope a silicone or thermoplastic elastomer with particles of a high relative permittivity. Various fillers have been tested, concentrating on various oxides, but also conductive polymer or metal nanoparticles [91–93]. Since these approaches have often lead to a decrease in break-down strength and increases in dielectric loss, lately encapsulated particles or a combination of particles have come into focus as well [94–96]. Because the fillers cause a stiffening of the material, recently silicone-based polymer blends (instead of composites) have been reported by Carpi et al. [97] with increased relative permittivity but a reduced stiffness at the same time.

In another approach, a modified version of the acrylic VHB 4910 was presented by Pei et al. [98,99]. An interpenetrating polymer network (IPN) is used to maintain the necessary pre-stretch partially. This leads to lower viscoelastic effects and a lower glass transition temperature (larger operating temperature range), while maintaining the good activation performance. Area strains up to 300 % were reported.

### 2.2.2 Compliant electrodes

Electrode materials for the application on DE transducers need to feature a good conductivity even when stretched. A large compliance is required for not inhibiting or reducing the active strain of the dielectric membrane. Carbon grease (carbon particles dispersed in silicone based oil) was used very commonly as electrode material [87,98,100,101]. Also loose carbon powder was used frequently, due to the easy handling and availability at a low price [102,103]. Carpi et al. have compared carbon grease electrodes to several others, including graphite powder, graphite spray and an electrolyte solution [104]. Carbon nanotubes (CNT) were investigated as electrodes as well (Fig. 2.3(a) [105]). Yuan et al. [105] showed that CNT electrodes could improve the life-time of actuators. In
2. Dielectric elastomer transducers

the area around a dielectric break-down the electrode burns away and leaves an insulated area, so that the actuator will continue to function with an insignificantly reduced active area. An improved version with CNT in combination with silicone oil was presented [106]. A micro-patterned silicone with sputtered silver electrodes was developed by Benslimane et al. [107]. Although the silver film itself is not very compliant, the corrugation of the surface allows the film to be stretched up to a certain point without breaking the electrode. Rosset et al. have published results on ion implanted metal electrodes, with promising results for micro-actuators [108] (Fig. 2.3(c)). The proof-of-concept for actuators without electrodes but with charges sprayed onto the surface (Corona charging) of a DE has been published lately by Kaltenbrunner et al. [109] (Fig. 2.3(b)).

Figure 2.3: (a) Self-healing electrodes of carbon nanotubes [105], (b) Electrode-free circular actuator [109], (c) Ion-implanted electrodes [108].

2.3 DE actuators

The simple structure of dielectric elastomers allows for a wide range of actuator designs [1,89,110]. The structure allows a scalability to large-scale or micro-scale actuators, which is almost unique. Since the polymers are soft and compliant, the actuators can easily adapt to various
shapes and surfaces. The elastomers are mostly transparent. Depending on the electrode material or the set-up, this transparency can be used in the application. The actuators can act at the same time as structural or protective membrane or even as sensor (Section 2.4). Some of the basic designs are shown in the following sections. Two general types of actuators can be distinguished, the contracting or stacked actuators and the expanding actuators.

2.3.1 Contracting configurations

Stacked actuators consist of many (often several hundreds or thousands) active layers and the contraction in thickness is the required outcome. They are made from non-prestretched material and can transmit the electrostatic force directly onto an object. Several stacked, folded and helical designs have been reported using silicone films mostly (Fig. 2.4(a)-(c)). Some of the designs that have been reported recently include stacked actuators for the use in micro-systems [111,112], and stacked actuators for tensile force transmission made of IPN-VHB material [102] (Fig. 2.4(d),(e)). One of the main issues is the manufacturing of these devices and automatic processes with spin coating or slot coating of silicones and printing or spraying of electrodes have been reported [111].

2.3.2 Expanding configurations

Expanding actuators often work with a surrounding mechanical structure and mostly in a pre-stretched configuration, since a thin film cannot exert any force otherwise. They can be divided in three main groups: (i) Planar actuator designs for linear or biaxial displacement (Fig.2.5), (ii) Non-planar actuator designs for linear displacement (Fig.2.6), (iii) Actuators for out of plane displacement (Fig.2.7).

(i) The most common planar membrane actuator is the circular actuator, which is maybe the simplest design and was often used as a demonstrator and for material characterization and evaluation. Also often used for performance evaluation (isometric or isotonic) was the square planar actuator with linear activation [87]. Further examples of planar membrane actuators are the bow-tie [66], and the diamond-shaped [72] actuators. There are also several push-pull configurations, where two actuators work...
Figure 2.4: Various designs of contracting actuators. (a) Stacked actuator [113], (b) Folded actuator [113], (c) Helical actuator [113], (d) Stacked actuators for micro systems [111,112], (e) Stacked actuators for tensile force transmission [102].

(ii) There are several actuator designs in which the actuators are not arranged in plane, but that still serve as liner actuators. A well-known example is the spring-roll actuator [66,115]. Lately a core-free rolled actuator was presented made with IPN-VHB material (Section 2.2.1) [116]. A very similar example is the tube actuator [117]. The spider actuator exerts a linear displacement, but is actually contracting when activated [66]. An out-of-plane push-pull configuration was presented with the universal muscle actuator [118]. There are various bubble designs and diaphragm actuators [66]. Bistable rigid-to-rigid bubble actuators with thermoplastic dielectric material were presented, where the material is heated, deformed by applying an electrical field, and then cooled again [119]. This “freezes” the actuator in the deformed position and it can be touched without any risk. The same advantage is offered by the DE actuators based on hydrostatic coupling [120]. A passive membrane that can be touched is coupled to an active membrane by an incompressible fluid which transfers the force and motion (Fig. 2.6).
(iii) Several bending actuators were developed, e.g. multi-degree-of-freedom spring roll or spine actuators [62]. An inflated bending cylinder was presented and an inflated balloon actuator [8]. Several shell-like actuators were built by Lochmatter [121]. He also introduced an active agonist-antagonist hinge configuration with planar membrane actuators. With this a shell-like actuator configuration was built that consisted of many agonist-antagonist segments. With the right control mode an undulating, fish-like movement was acquired [121]. The same hinge config-
Figure 2.6: Various actuator designs for linear displacement. (a) Spring-roll actuator [8], (b) Core-free rolled actuator [116], (c) Tube actuator [117], (d) Spider actuator [66], (e) Universal muscle actuator [118], (f) Diaphragm actuator [66], (g) Bistable rigid-to-rigid bubble actuator [119], (h) Hydrostatically coupled actuator [120].
2.3. DE actuators

Figure 2.7: Various actuator designs for out-of-plane motion. (a) Multiple-degrees-of-freedom spring-roll actuator [62], (b) Multiple-degrees-of-freedom spine-roll actuator [62], (c) Inflated bending tube actuator [8], (d) Balloon actuator [8], (e) Biaxial bending actuator with core of spheres [121], (f) Shell-like DE segment construction for continuous wave-like motion [121], (g) Model airship with active hinge rudders [122], (h) DE minimum energy structure [83].
2.4 DE sensors

Another possible application is to use DE as sensors. When a charged DE device is strained or contracted, the capacity and the serial resistance within the electrodes change and we can deduce the deformation from these changes. Lifetime and reliability are still challenging with the dielectric membranes though and may therefore be critical for the application as sensors, since the behaviour tends to change with time. Still, the interesting aspect is that one and the same element can be used as sensor and actuator [103, 124–126]. The application, handling and design of the device is potentially much easier than with common strain gauges, which are often rigid and fragile.

2.5 DE generators

Dielectric elastomers can also be used to convert mechanical work into electrical energy [127]. The advantage is that this type of generator can directly be coupled to the low-frequency motion of e.g. ocean waves, human body movement, or the wind. Additionally, the material is soft and offers a great flexibility in shape and design, while still offering a large energy density. We can discern three different possibilities to do so: a cycle with constant charge, with a constant voltage, or with a constant electrical field. Four steps make up the energy harvesting cycle: 1. Mechanical stretching, 2. Electrical charging, 3. Mechanical relaxation, and 4. Energy harvesting (Fig. 2.8). In the constant charge cycle, the film is stretched, a voltage is applied, the source is removed and the elastomer is relaxed. During the relaxation the charge is forced apart and thus the potential between the electrodes is increased. For the constant voltage cycle the first two steps remain the same. Afterwards the DE is relaxed while keeping a constant voltage, therefore we have a discharging of the device and a current flowing. Similar with the constant electrical field. A recent study, the three cycles were analysed theoretically in order to find an optimum, but comes to the conclusion that an advantageous combination of these my be the best solution [128]. In either case the dielectric elastomer has to be charged first (even though the necessary voltages can be low, the efficiency may be better at a higher voltage level) and these devices are therefore often designated as an energy pump. Experimental results are available from a DE energy harvesting buoy, an energy scavenging device behind the knee, a generator within the sole of a shoe and
a device for manually pumping energy [129–131]. Some modelling has been done as well, including a study on the maximum possible energy that can theoretically be converted by a specific generator [132].

Figure 2.8: Working principle of a DE energy harvesting cycle with constant charge.
Chapter 3

Conceptional study and preliminary tests for a scalable actuator design

The actuator design is a result of the physical principle of actuation, the actuator material, the necessary output performance and boundary conditions (Fig. 3.1). While the physical principle of DEA is described in Chapter 5.3, materials, desired output and boundary conditions will be discussed in the following. The results of preliminary tests with small actuators on inflated structures (body segments) are illustrated and conclusions are drawn concerning the design of large-scale actuators.

3.1 Material and methods

3.1.1 Material and material preparation

As a dielectric membrane, VHB 4910 (1 mm) or VHB 4905 (0.5 mm) (by 3M) was used. It is the material that has shown the largest active strains, is commercially available in large amounts, is well characterized and has often been used for DE actuators and is therefore well-known (e.g. [1, 62]). The advantage of pre-stretching this material has been proved theoretically and in experiment [87, 88, 93]. The stretched material can withstand higher break-down fields, there is no or later loss
of tension at activation, the film is thinner, and an anisotropy can be introduced in the system, which allows for a primary direction of the extension. An optimal range of $\lambda_x = 2 - 4$ has been established [123]. The used pre-stretch was between $\lambda_x = 3, \lambda_y = 5$ and $\lambda_x = 3.5, \lambda_y = 6.5$ but is specified for each application. In some cases an 'excess' pre-stretch was used for coating the electrodes and applying internal reinforcements (Fig. 3.2(b)). Once the actuator is fabricated it is released a little bit to the pre-stretched state from which it is then activated (Fig. 3.2). The specific values for the stretches in Figure 3.2 are only examples.

In Chapter 2.2.2 an overview over existing electrodes for DEA is given. For all of the actuators described in the following, loose carbon powder (KetjenBlack EC600-JD by Akzo Nobel) was used. Very large areas can thus be covered easily and fast and no change in the conductivity over time is expected, since there are no solvents or other components involved that may evaporate. An exact description of the actuator fabrication is given in the Appendix A.

The boundary conditions are defined by a potential application and influence the parameters of the actuators. The desired outcome is often a certain activation strain and force difference at a certain applied electrical voltage and activation frequency. Since a planar membrane actuator cannot exert any force (and thus not produce any work) directly at activation, a whole activation cycle must be considered, where work is produced while the actuator is contracting. Often the actuators are arranged in an agonist-antagonist configuration therefore, where one actuator will contract, while the other expands. In the present case, the boundary conditions are given by the fish-like airship. The required per-
3.1. Material and methods

Figure 3.2: The undeformed elastomer membrane (a) is stretched to a state beyond the necessary pre-stretch for activation (b) it is coated with electrodes and necessary reinforcements or passive structures are applied. The actuator is then relaxed a bit to the necessary working pre-stretch (c) from where it is activated (d). The values for the stretches are only examples for clarification.

formance of the actuators include therefore the angle and force necessary to create a bending of the airship body and an attached caudal fin similar to a fish in steady motion. Further the actuators have to be light-weight, compatible with the helium-tight hull, a certain robustness and lifetime is required and the possibility for up-scaling has to be given. In order to test several actuator design concepts, preliminary tests with smaller actuators were done, some on inflated structures (body segments).

3.1.2 Measurement systems

The actuators on each side of a body segment were activated alternately with a square high voltage signal at a certain frequency. The high voltage amplifier was a Trek 5/80 (by BFI Optilas, Puchheim) unless specified otherwise. The voltage was switched by relays and controlled by a frequency generator (type 33120A by Hewlett Packard). The low voltage was either generated with LabView (by National Instruments) or provided by a voltage source (type Digistant 4411 by Burster). The voltage and the current signal were read out from the high voltage amplifier directly with LabView. The displacement was measured in three different ways, depending on the actuator structure and test-rig. Mostly, deflection angles ($\phi$) were measured directly with a Hall sensor (type QP-2HC-SW4 by Pewatron). Sometimes the strain ($s$) or displace-
Preliminary tests for a scalable DE actuator design

Displacement ($\Delta x$) was measured instead with a videoextensometer (minicam by Cervis, program by Labview, National Instruments) or a laser sensor (OADM 2016460/S14F by Baumer electric). In a hinge configuration, the conversion between displacement and angle can be calculated with an approximation (Eq. 3.1) for small angles and a large length-to-width-ratio ($D/W \geq 1$) (Fig 3.3(b)). The exact, more complex trigonometric relations can be found in Appendix C.

$$\varphi = \arcsin\left(\frac{2\Delta x}{W}\right) = \arcsin\left(\frac{\Delta L}{W}\right)$$  \hspace{1cm} (3.1)

The blocking force was measured by blocking the displacement of the agonist-antagonist system with a force gauge (type S2, 20 N = 2mV/V by HBM) at one end, either blocking it directly or with a stiff connection between the passive structure and the force gauge. Only the according opposite actuator is activated (Fig 3.3(c)). The blocking moment ($M$) or the blocking moment per unit height ($m$) can then be calculated from the blocking force ($F_{meas}$).

$$m = \frac{M}{H} = -\frac{F_{meas} \cdot D}{H} = \frac{W(F_{passive} - F_{active})}{2H}$$ \hspace{1cm} (3.2)

Figure 3.3: Agonist-antagonist structure with hinge (Top view). (a) Deflection angle measurement, (b) Blocking force measurement.
3.2 Preliminary actuator designs and performance evaluation

Large deflection angles and blocking moments are the desired output parameters. They are recorded over varying activation voltages and activation frequencies. Three different general solutions for the actuators can be distinguished:

1. A fully integrated version, where the actuators are part of or glued directly onto the gas-tight envelope (Section 3.2.1, Fig. 3.4(a)). This leads to a destruction of DEA and hull at removal. This will be called ‘fully integrated’ solution throughout the Section.

2. The actuator is mounted on an auxiliary structure around or between the inflated body or bodies. At removal the DEA will be destroyed but not the hull (Section 3.2.2, Fig. 3.4(b)). These actuators will be named ‘partially integrated’.

3. The actuator is completely independent of the inflated body. It is removable for storage or exchange and reusable. (Section 3.2.3, Fig. 3.4(c)). It will be called ‘independent’ actuator.

Preliminary tests for all of these versions were done and are described in the following Sections. A summary of the advantages and disadvantages is given in Section 3.3.

Figure 3.4: (a) Fully integrated solution. (b) Separate inflated bodies connected by DE actuators. Actuators can be removed without destroying the hull. (c) Independent actuator-hull system with removable actuators. [133]
3. Preliminary tests for a scalable DE actuator design

3.2.1 Hull–actuator interaction and fully integrated DEA

To investigate the interaction between the membrane actuators and the hull, a biaxial test-stand was designed (Fig. 3.5(a)) [134]. The weights attached to the four arms introduce the biaxial stress in the membrane representing the stress from the internal pressure and can be varied. In the center, a square actuator of 0.14x0.14 m was stuck to the membrane in an over-stretched state (Fig. 3.6, Point 1. Fig. 3.2(b)). When released from the auxiliary frame the actuator contracts to the pre-stretch state and the gas-tight membrane below wrinkles (Fig. 3.6, Point 2). From there the actuator expands at activation (Fig. 3.6, Point 3). For a given over-stretched state \( \lambda_{ops}^x \), the pre-stretch \( \lambda_{ps}^x \) can be chosen in a way that in a fully activated state, the hull beneath is still wrinkled \( (2a \rightarrow 3a) \) or that at the fully activated state the hull is just stretched \( (2b \rightarrow 3b) \). If the pre-stretch is too close to the over-stretched state then the hull actuator is stretched completely before the full active strain is reached and any further expansion is blocked \( (2c \rightarrow 3c) \). The load of the internal pressure is then completely absorbed by the hull membrane. The active strains were measured with a videoextensometer at various loads and the results are shown in Figure 3.7. Actuator 10 was measured with an over-pre-stretch of \( \lambda_{ops}^x = 6, \lambda_{ops}^y = 3 \) (Fig. 3.7(c),(d)). When we compare the active strains to actuator 8 with \( \lambda_{ops}^x = 6, \lambda_{ops}^y = 6 \), we can see that larger expansions are reached with actuator 8 at a low force in the active x-direction (Fig. 3.7(a),(b)). Qualitatively it was noticed that the wrinkling of the membrane varied a lot and influenced the outcome considerably, generating results with poor reproducibility. With a zig-zag borderline of the electrode the wrinkling of the hull was influenced, such that it would fold like a fan (Fig. 3.5(b)). This lead to slightly better results (Actuator 13, Fig. 3.7(e),(f)), but still not satisfying reproducibility. From this the conclusion can be drawn that any adhesion between hull and actuator in the active direction has a negative influence on the active deformation. Therefore the actuators on the final inflated hull should not simply be square but feature a shape corresponding to the deformation field (e.g. like a lemon slice) thus avoiding such a bonding surface. It was observed that the actuators often failed mechanically or electrically through friction of stress peaks caused by the wrinkles in the hull. Additionally, the ratio of the pre-stretch in x- to the pre-stretch in y-direction cannot be chosen freely, since they are dependent on the internal pressure and their ratio is dependent on the shape of the inflated
3.2. Preliminary actuator designs and performance evaluation

body.

Figure 3.5: (a) Biaxial test stand for investigating the hull-actuator interaction. (b) Special borderline of the active zone for more regular wrinkling of the hull.

Figure 3.6: Schematic description of the activation characteristics of the biaxial test-stand. 1: Over-pre-stretched state (manufacturing), 2: Prestretched state at \( V = 0 \), 3: Activated state at \( V > 0 \).

Nevertheless, preliminary qualitative tests were made on an inflated hull segment with actuators applied directly onto the membrane (Fig. 3.8).
Challenges include mainly the application of the pre-stretched actuators from the auxiliary frame onto the inflated tube. Further, the internal pressure decreased with time and the distance between the hinge point and the actuator decreases therefore. If the restoring moment becomes too small, the segment will stay deflected. Asymmetric actuators were tested to resolve this problem, which worked well (Fig. 3.8(b)). The main disadvantage of this fully integrated solution is the large number of actuators that failed mechanically during the application on the segment and the failure through friction or mechanical stress peaks through the wrinkling membrane below. This was even more critical than on the
bi-axial test-stand due to the large curvature and the internal pressure, pressing the hull against the actuator. The scalability may prove difficult as well, since the actuator needs to cover the entire side of the hull for geometrical reasons. By splitting the actuators in parts, the challenge of a bonding surface in the active direction will have to be addressed, just as with the square actuators of the bi-axial test stand. In a preliminary test,

![Image](image1.png)

Figure 3.8: Membrane actuators fully integrated on inflated hull segment. (a) Symmetric actuators (top view). (b) Asymmetric actuators (side view).

Two inflated segments were connected by a square actuator (Fig. 3.9). This possibility was not further considered because the pre-stretch of the actuator presses the two segments against each other making a deflection almost impossible. A rigid connection between the segments may solve this problem. This alternative was dismissed nevertheless because it would lead to large losses in volume and therefore lift and moreover cause additional weight.

![Image](image2.png)

Figure 3.9: Two inflated segments connected by a DE actuator.
3.2.2 Partially integrated DEA on a bending structure

It was decided that tests should be done without the hull–actuator interaction, simulating a rigid outer structure supporting the actuators [135]. Figure 3.10 shows the segment and the actuator applied to it. The actuator is split in five smaller actuator segments with a passive zone (10 mm) between them where the supporting carbon rods lie. The pre-stretch at fabrication was chosen at $\lambda_{ops}^x = 3.3, \lambda_{ops}^y = 6.3$, considering that the actuator would contract slightly in both directions and the remaining pre-stretch should not be below $\lambda_{ps}^x = 3, \lambda_{ps}^y = 6$. One and two-layered actuators were applied to the body segment and actuated alternately (as described in Section 3.1.1). The resulting deflection angles are shown in Figure 3.11. The decrease in the deflection with increasing frequency is due to the viscoelastic material characteristics. The increase at 1 Hz is a resonance effect (Fig. 3.12). This is more pronounced for the one-layer segment, since the mass is different for the two-layer segment and the resonance peak shifted therefore. We observe a slight decrease of the deflection from the one- to the two-layered segment. This may be because the forces from the pre-stretch are doubled and the actuators actually started to delaminate from the frame, thus loosing pre-stretch. The results of the blocking force measurements at 0.2 Hz are shown in Figure 3.13. About twice the blocking force is reached with a two-layered actuator, as expected. Again, a delamination of the actuators my have lead to a reduced pre-stretch and thus to a slightly lower result.

This solution where the actuator stretch is independent of the hull
3.2. Preliminary actuator designs and performance evaluation

Figure 3.11: Deflection angle vs. frequency at different voltages. One- and two-layered segment.

Figure 3.12: Deflection angle vs. time over a frequency sweep.

shows a better performance than the fully integrated solution and the lifetime of the actuators was better and more controllable. The scalability of the area is given (many small patches are easily possible), but scaling the number of layers of DE and therefore the blocking moment is difficult. Even at two active layers, the adhesion to the carbon rods was
3. Preliminary tests for a scalable DE actuator design

3.2.3 Independent actuators on an inflated hull segment

Actuators were developed that can be removed and replaced on the hull without damaging the actuator or the hull \[136\]. For testing, an inflated body segment was used with an inner structure, like a keel or the skeleton in the fish. The advantage of this option is that a fish-like shape (lens-shaped cross-section) could be achieved, which allows for easier bending of the segment (larger angles at smaller strains). Some of the pre-stretch force can be transferred from the hull onto the inner structure. In order to avoid friction between hull and actuator, a recess was left between actuator and hull, like a contraction in the hull (Fig. 3.14). The actuators were reinforced internally with glass-fiber-composite (GFC) rods (1 mm diameter). In order to protect the membrane from being punctured, the ends were rounded with a drop of hot glue (Fig. 3.15). For the one-layered actuators, two layers of VHB 4905 were coated on one side with

Figure 3.13: Blocking force vs. activation voltage. One- and two-layered segment.

not very good and at four layers the actuator could not be fixated at all. This could be solved with an increase of the number of carbon rods, but even as it is, this solution is already critical concerning the weight for the application on a model airship.
3.2. Preliminary actuator designs and performance evaluation

Inflated hull Actuators

Figure 3.14: (a) CAD of the segment (b) top view of the segment with recess between hull and actuator (c) side view.

electrode material and glued together with the GFC rods in between, for a symmetric configuration. The pre-stretch of the membrane was \( \lambda_x = 3.3 \) in the active direction and \( \lambda_y = 6.3 \) in the passive direction. The pre-stretch in the y-direction of these actuators is completely independent of the hull, while the pre-stretch in the active x-direction is partially dependent on the internal pressure of the body segment. They can be taken away for storage in a half-relaxed state in the x-direction. Table 3.1 shows the different actuators that were measured. The active area of actuators 1.2, 3.2, and 5.1 is \( 333 \times 176 \) mm (Fig. 3.15(a)). One-, two- and three-layered actuators were compared. To enable an up-scaling, taking into account the maximum length of 1 m of the pre-stretching device, actuators were tested that were only half as high but of the same length (actuator 4.1) (Fig. 3.15(b)).

Figure 3.15: (a) Actuator with internal GFC-rod-reinforcement \( 0.333 \times 0.176 \) m (b) \( 0.333 \times 0.088 \) m.
Table 3.1: Actuators that were tested on the inflated hinge segment with inner structure. Resulting deflection angle and blocking moment at 0.2 Hz and 3 kV.

<table>
<thead>
<tr>
<th>Actuator No</th>
<th>Active layers</th>
<th>Active area</th>
<th>Deflection angle</th>
<th>Blocking force</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>1</td>
<td>0.333x0.176 m</td>
<td>6.5°</td>
<td>0.10 N</td>
</tr>
<tr>
<td>3.2</td>
<td>2</td>
<td>0.333x0.176 m</td>
<td>9.0°</td>
<td>0.34 N</td>
</tr>
<tr>
<td>5.1</td>
<td>3</td>
<td>0.333x0.176 m</td>
<td>11.1°</td>
<td>0.66 N</td>
</tr>
<tr>
<td>4.1</td>
<td>2</td>
<td>0.333x0.088 m</td>
<td>5.9°</td>
<td>0.24 N</td>
</tr>
<tr>
<td>7.1</td>
<td>2</td>
<td>0.190x0.176 m</td>
<td>8.7°</td>
<td>0.40 N</td>
</tr>
</tbody>
</table>

Figure 3.16: (a) Tilting of the internal reinforcement, (b) Reinforcement at an angle, (c) Square reinforcements to interrupt the tilting, (d) Actuator strutted against hull in the middle.

The smaller actuators (type actuator 4.1) turned out to be unstable. The reinforcement tended to tilt to one side, leaving areas with no pre-stretch and areas with too much pre-stretch (Fig. 3.16(a)). This effect was slower for two-layered actuators, therefore only results could be gathered for these. Even so they did not last longer than a day or two, before instability occurred. This problem was approached with various actuator designs (Fig. 3.16(b)-(d)), but only a short prolongation of the lifetime was attained. The deflection angle at 3 kV is plotted versus the activation frequency in Figure 3.17. The angle surprisingly increased with increasing number of layers, which indicates that an external moment needs to be overcome. Presumably this has to do with friction between the actuators and the hull and a bending resistance of the inflated segment itself. With actuator 4.1 similar deflection angles were obtained as with actuator 1.2, as expected. It is unfavourable however
because of an increase in weight and shorter lifetime. A strain measurement in addition to the angle measurement revealed that the outer part of the actuator was scarcely displaced, which leads to the assumption that a shorter actuator, spanning exactly the recess in the hull, would lead to the same deflection angles (Actuator 7.1, Table 3.1). This is confirmed in Figure 3.17. The blocking force and the blocking moment per unit height are shown in Figure 3.18. As expected, the blocking moment increases with the number of layers. The shorter actuator 7.1 produces a blocking moment in the same range as actuator 5.1, which is also expected. The blocking moment of the actuator of half the height (actuator 4.1) shows a higher blocking force than the one-layered larger one. It is at around one-third of the blocking force of the three-layered actuator 5.1 though and lies in the range of variation due to manufacturing.

![Figure 3.17](image.png)

**Figure 3.17:** Comparing the deflection angle of actuators of 0.333x0.176 m (1-3 layers), 0.333x0.088 m (2 layers), and 0.19x0.176 m (2 layers) at 3 kV.

### 3.3 Conclusions

A solution is aspired for the up-scaled actuators where the actuators are completely independent of the hull. The qualitative performance of each solution concerning specific aspects are summarized in Table 3.2. A more detailed description is given in the following Sections.
Figure 3.18: Comparing the blocking moment of actuators of 0.333x0.176 m (1-3 layers), 0.333x0.088 m (2 layers), and 0.19x0.176 m (2 layers).

Performance

For the fully integrated actuators on a hull-segment, no angle measurements were made. We can calculate an angle from the results of the biaxial test-stand, but the boundary conditions are isotonic and not an agonist-antagonist configuration. Still it can be said, that the fully integrated actuators performed well: a maximum strain of 25.7 % was measured for Actuator 8 at an optimal ratio of the membrane stress. The results are not reproducible though and the scatter is enormous. Also, this maximum active strain is reached for a certain boundary condition (for a certain membrane stress), which we cannot be sure to achieve on an airship through internal pressure alone. A maximum angle of 13° was reached with the partially integrated one-layered actuator on an external structure. In these tests the influence (friction, bending resistance) of a hull was completely omitted. The same angles were reached with an independent three-layered actuator. The blocking moment with a one-layered actuator is about three times as high for the actuator on an external structure (Section 3.2.2) than for the fully independent solution (Section 3.2.3). One reason is that any external friction or drag of the hull is neglected in the system with the ribs. Also, the actuators are attached slightly further from the internal back-bone structure, while this
distance is dependent of the internal pressure for the latter solution.

**Actuator-Hull interaction**

The fully integrated actuator cannot be removed from the hull without destroying the actuator and eventually causing damage to the hull. The pre-stretch is dependent on the internal pressure in both directions. It was noticed that the active deformation is greatly impaired through friction between hull and actuator and especially in the place where the border is attached onto the hull. For the partially integrated actuator, the pre-stretch is completely independent of the internal pressure. At removing the actuator, it will be destroyed, but no damage to the structure or the hull is done. An unsolved challenge remains, how the carbon rods would be attached to the inflated body or to an internal structure while maintaining the system helium-tight. The independent actuator can be exchanged and removed without breaking the hull or the actuator. The pre-stretch is dependent on the internal pressure, but only in the active direction. Friction between hull and actuator impair the active deformation, which can be compensated with a constriction in the hull where the actuators are.

**Scalability**

Since the bonding surface between hull and actuator for the fully integrated version leads to large impairment and bad reproducibility of the deformation, we would like to have a lens-shape (like a lemon slice). Since the airship may be more than a meter high though, the scalability is not feasible as hoped. The scalability in area is easy for the partially integrated solution, but the scaling of the number of layers proved difficult (delamination of the actuator from the structure). An increase in the number of carbon rods may solve this problem, but leads to an increase in weight. The scalability for the independent actuators should be given, although the length-to-height-ratio should not exceed two. The stiffness of the internal reinforcement must be scaled with the size of the actuator.

**Durability**

The fully integrated actuators were durable, while just immobile on the completely stretched hull. This is not a realistic condition and they were
often damaged during activation through friction between hull and actuator. The partially integrated actuators started to delaminate from the supporting structure after only few days and many actuators were destroyed in the course of attaching them onto the structure. The independent actuators lasted around six days usually, before the elastomer mechanically failed at the stress peaks at the end of the internal reinforcements.

### Weight

The weight of the fully integrated solution is optimal, it is limited to the minimum necessary material. The partially integrated solution consists of an internal backbone-structure and carbon rods that exceed the length of the actuator. Additionally the fixation between carbon rods and actuator and hull add to the weight. The independent solution features the internal reinforcing rods that add to the extra weight, but are restricted to the actual size of the actuator itself.

Table 3.2: Comparing the different actuator designs with regard to various aspects.

<table>
<thead>
<tr>
<th>Regarding</th>
<th>Fully integrated</th>
<th>Partially integrated</th>
<th>Independent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Actuator-Hull interaction</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Scalability</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Lifetime</td>
<td>-</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Weight</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>
Chapter 4

Large actuators for the application on an inflated body

In an iteration between aerodynamics (necessary deformation) and aero-statics (lift and size) of the airship, a necessary size of the actuators needed to drive the airship was determined (see Chapter 6.3). With the demand for square-meter-sized actuators, several questions arise as a consequence. Since actuators of this size had not been presented before, the main question arises, whether they scale and perform as expected. In the design of planar actuators for realistic applications, one of the major challenges is generally maintaining the mechanical pre-stretch whilst avoiding impairment of the deformation, and even more so for large-scale, light-weight actuators. Other problems that may be expected from the scaling include large stress peaks at the edges and stiff structures, a higher break-down rate due to a higher probability for defects in the membrane, and a different (slower) time-dependent behaviour due to the larger area of the capacitor. This Chapter is based on the publication "Scaling of planar dielectric elastomer actuators in an agonist-antagonist configuration" [137].
4.1 Scaling of the DE actuators

The investigation of the scaling behaviour of planar membrane DE actuators is based on actuators on an active hinge as published in [100]. The actuators on the small hinge measure 0.19 m in height \((H)\) and 0.05 m in length \((L)\). An overview over the theoretical scaling of different parameters is presented first. The scaling factors \(S\) and \(n\) are introduced for planar dimensions and number of layers respectively. The small actuators are scaled in the planar dimensions by a factor \(S = 5\) to 0.95 x 0.25 m (Table 4.1). The thickness of the dielectric membrane or the electrodes is not scaled in order to ensure that the electric field remains unchanged. The total thickness of the actuator is scaled by the number of layers with a factor \(n = 3\). The actuators are experimentally characterised on a planar test-rig that can be compared to the hinge configuration (Section 4.1.3, Fig. 4.5). The corresponding deflection angle and blocking moment of an equivalent hinge are calculated with simple trigonometry from the measured strain and blocking force (Section 3.1.1, Eq. 3.1, 3.2). Furthermore the input voltage and current is monitored and some electro-mechanical properties are evaluated.

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Small actuator</th>
<th>Large actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions Active Area (Length L, Height H) [m]</td>
<td>0.05x0.19</td>
<td>0.25x0.95</td>
</tr>
<tr>
<td>Dimensions Total (including passive material and stiff structure at the edges) [m]</td>
<td>0.055x0.20</td>
<td>0.32x0.98</td>
</tr>
<tr>
<td>Hinge width (W) for calculating deflection angle/blocking moment [m]</td>
<td>0.03</td>
<td>0.15</td>
</tr>
<tr>
<td>Pre-stretch ((\lambda_p^x, \lambda_p^y)) [-]</td>
<td>3x5</td>
<td>3x5</td>
</tr>
<tr>
<td>Number of dielectric layers [-]</td>
<td>1 or 3</td>
<td>3</td>
</tr>
<tr>
<td>Weight active material per layer per side of the hinge [g]</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>

4.1.1 Theoretical aspects of DE scaling

The dependence of various actuator parameters on the size is summarised in Table 4.2. The scaling factor is expressed in \(S\) for planar dimensions and \(n\) for the number of layers.
Table 4.2: Theoretical scaling of several parameters with $S$ as scaling factor of the planar dimensions and $n$ as scaling factor in the thickness (number of layers).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free strain [-]</td>
<td>$s_{\text{large}}/s_{\text{small}} = S^0 = 1$</td>
</tr>
<tr>
<td>Deflection Angle [rad]</td>
<td>$\varphi_{\text{large}}/\varphi_{\text{small}} = S^0 = 1$</td>
</tr>
<tr>
<td>Blocking force [N]</td>
<td>$F_{\text{large}}/F_{\text{small}} = S \cdot n$</td>
</tr>
<tr>
<td>Blocking moment [Nm]</td>
<td>$M_{\text{large}}/M_{\text{small}} = S^2 \cdot n$</td>
</tr>
<tr>
<td>Capacitance [F]</td>
<td>$C_{\text{large}}/C_{\text{small}} = S^2 \cdot n$</td>
</tr>
<tr>
<td>Sheet resistance [Ω/□]</td>
<td>$R_{S,\text{large}}/R_{S,\text{small}} = S^0 = 1$</td>
</tr>
<tr>
<td>Time constant [s]</td>
<td>$\tau_{\text{large}}/\tau_{\text{small}} = S^2 \cdot n$</td>
</tr>
<tr>
<td>Input energy [J]</td>
<td>$W_{\text{in,large}}/W_{\text{in,small}} = S^2 \cdot n$</td>
</tr>
<tr>
<td>Output work [J]</td>
<td>$W_{\text{out,large}}/W_{\text{out,small}} = S^2 \cdot n$</td>
</tr>
<tr>
<td>Efficiency [-]</td>
<td>$\eta_{\text{large}}/\eta_{\text{small}} = S^0 = 1$</td>
</tr>
</tbody>
</table>

**Free strain/Deflection angle**

The free strain $s = \Delta L/(2 \cdot L)$ is measured ($\Delta L$ being the difference in length between the expanded and the contracted actuator, Section 3.1.1, Fig. 3.3). For small width/length ratios the deflection angle can be approximated by $\varphi = \arcsin(\Delta L/W)$. Free strain and deflection angles are not expected to change with the size or number of layers of the actuator as long as the geometry is similar. The ratio between length ($L$) and width ($W$) of the hinge has an influence on the deflection angle $\varphi$, but is kept constant for this study.

**Blocking Force/Moment**

The blocking force of the passive actuator can be calculated with $F_{x,\text{passive}} = H \cdot n \cdot t \cdot \sigma_x$ ($\sigma_x$ being the Cauchy stress in the direction of deformation of the passive actuator). The activated film expands in the planar directions due to electro-mechanical compression in the thickness direction. The equivalent pressure $p_{eq}$ acting on the elastomer membrane can be calculated for a given activation voltage $V$ with $p_{eq} = \varepsilon_0 \cdot \varepsilon_r \cdot (V/t)^2$ (Section 2.1, [69]). The blocking force of the activated actuator can thus be calculated with $F_{x,\text{active}} = H \cdot n \cdot t \cdot (\sigma_x - p_{eq})$. This adds up to a moment $M$ (Eq.4.1)

$$M = (F_{\text{passive}} - F_{\text{active}}) \cdot \frac{W}{2} = n \cdot H \cdot t \cdot \frac{W}{2} \cdot \varepsilon_0 \cdot \varepsilon_r \cdot \left(\frac{V}{t}\right)^2 \quad (4.1)$$
Force scales with the cross-section of the actuator \((S \cdot n)\), which is dependent on the number of layers \((n)\), the thickness per layer \((t)\) and the height \((H)\) of the actuator. The bending moment is additionally dependent on the width of the hinge \((W)\) (scaling factor: \(S^2 \cdot n\)).

**Output work**

The output work of a hinge is the product of blocking force and displacement or moment and angle \((W_{\text{out}} = \Delta F \cdot \Delta x = M \cdot \varphi)\) and it scales therefore with height \(H\), number of layers \(n\), thickness of layers \(t\) and the active length of the actuator \(L\) (scaling factor: \(S^2 \cdot n\)). In the linearised scheme (Fig. 4.1) point 1 designates the state when both actuators are deactivated. In point 2, actuator 2 is activated while actuator 1 remains passive. The voltage is then switched, actuator 1 is activated, actuator 2 is deactivated and by following the arrows, point 3 is reached. The enclosed hatched area designates the output work of the agonist-antagonist system. Apparently this work corresponds to the work produced by a single actuator in a work cycle given by point 2-2’-3-3’ (grey area).

![Diagram of output work in an agonist-antagonist system](image)

Figure 4.1: Linearised schematic of the output work in an agonist-antagonist system.

**Input energy**

The energy that is needed to charge the actuator can be calculated from the capacitance. Figure 4.2 shows an example for the typical charging characteristics of a DE actuator. The charge is equal to the area beneath
4.1. Scaling of the DE actuators

the dashed current progression \( Q = \int_{t_0}^{t_1} i(t) \, dt \). The input energy is then calculated with \( W_{in} = \int_{t_0}^{t_1} u(t) i(t) \, dt \). The capacitance of the actuators scales with the area of the actuator \( (C = \varepsilon_0 \cdot \varepsilon_r \cdot A/t) \). An n-layered actuator is equal to \( n \) capacitors in parallel and the capacitance scales also with the number of layers \( n \). Therefore the input energy scales - like the capacitance - with the active height, active length and the number of layers (Scaling factor: \( S^2 \cdot n \)).

Figure 4.2: Linearised schematic of the output work in an agonist-antagonist system.

**Time dependency**

The time-dependent behaviour can be influenced e.g. by:

- Inertial forces \( m \cdot a \) which are presumably very small for the planar test rig and have been neglected.

- Viscosity of dielectric membrane (stretching rate), which is modelled e.g. with a Prony series. Viscosity plays a major role for the acrylic VHB 4910, and was accounted for by comparing all results after the same activation period of 5 s.

- Sheet resistance of electrode and electrical connections (leads). The ohmic sheet resistance \( R_S = \rho/d = R \cdot L/H \) remains constant; while the length \( (L) \) increases also the cross-section (with the height \( H \)) increases by the same amount (with \( \rho \) being the
specific resistivity, and $d$ the electrode thickness). The lead is critical for the resistance and electrical connections onto the electrode, which need to be enlarged accordingly. The time constant $\tau$ defined as $\tau = C \cdot R$ scales therefore with $S^2 \cdot n$.

### Efficiency

Because in theory input energy and output work both scale with $S^2 \cdot n$, the efficiency $\eta = W_{out}/W_{in}$ remains constant when scaling. Friction, mass effects, electrical losses (leakage current) and viscous losses may have a negative influence though and vary with size. For our modelling all of these effects were neglected.

### Modelling

To investigate whether we can use established models for large-scale actuators, the Arruda-Boyce form for the strain energy potential (Eq.4.2) was used to model the deflection angles. The material parameters were taken from Wissler et al. [80] (Table 4.3). A permittivity of $\varepsilon_r = 3.2$ was used for the calculations, since the material parameters have been established for this value, although a different permittivity was measured later (see Chapter 5.2.2).

\[
W_{\text{Arruda-Boyce}} = A \cdot \left[ \frac{1}{2} (I_1 - 3) + \frac{1}{20N} (I_1^2 - 9) + \right. \\
\left. + \frac{1}{1050N^2} (I_1^3 - 27) + \frac{1}{7000N^3} (I_1^4 - 81) + \frac{1}{673750N^4} (I_1^5 - 243) \right] \quad (4.2)
\]

The viscoelastic time-dependent behaviour of the VHB was described with the Prony series (Eq.4.3) where $g_k$ and $t_k$ are material constants (Table 4.3). Another approach is a simple Kelvin-Voigt model (Eq.4.4) where $\tau_R$, $\varepsilon_\infty$, and $\varepsilon_0$ are independent fitting parameters (using $\tau_R = 1$, $\varepsilon_\infty = 2$, and $\varepsilon_0 = 1$).

\[
g(t) = 1 - \sum_{k=1}^{n} (g_k \cdot (1 - exp(-\frac{t}{t_k})) \quad (4.3)
\]

\[
g(t) = \varepsilon_0 + (\varepsilon_0 - \varepsilon_\infty) \cdot exp(-\frac{t}{\tau_R}) \quad (4.4)
\]

A logarithmic fit for the results in this frequency-range as a third possibility is shown in Equation 4.5 for $a = 0.2017$ and $b = 0.6995$. This is
then not an independent material model, but simply a fit to our data of course.

\[ g(t) = a \cdot \ln(t) + b \]  \hspace{1cm} (4.5)

Table 4.3: Parameters of the Arruda-Boyce model with Prony series for VHB 4910 (Wissler, Mazza [80]).

<table>
<thead>
<tr>
<th>A</th>
<th>N</th>
<th>g1</th>
<th>t1</th>
<th>g2</th>
<th>t2</th>
<th>g3</th>
<th>t3</th>
<th>g4</th>
<th>t4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0473</td>
<td>124.88</td>
<td>0.452</td>
<td>0.341</td>
<td>0.144</td>
<td>2.326</td>
<td>0.0746</td>
<td>33.07</td>
<td>0.0215</td>
<td>313.8</td>
</tr>
</tbody>
</table>

4.1.2 Actuator designs

As described in Section 3.1.1, the actuators were made of pre-stretched VHB 4910 ($\lambda_x^{ps} = 3, \lambda_y^{ps} = 5$) with rubbed carbon particle electrodes. Lochmatter et al. used the same pre-stretch and dimensions for the active hinge in [100]. The actuators were fixed on the stiff hinge structure on both sides with a free end on the top and bottom side where the elastomer contracted due to the pre-stretch (Fig. 4.4). The electrical connection was made with a metal tape with a conductive adhesive side (Scotch 1183 by 3M) (see Appendix A).

Although the overall mechanical stresses from pre-stretching the dielectric material theoretically remain unchanged for up-scaled actuators, local stresses due to boundary conditions often lead to premature mechanical failure of the membrane. More attention must be paid to details in the design to impair these local defects. Three concepts were tested for a large-scale actuator: The first actuator design consists of a membrane, which is internally reinforced with carbon rods every 5 cm, such that the distance between the rigid reinforcements stays the same as in the small hinge (Fig. 4.3(a)). In the second design, the contraction or tearing of the membrane is restrained with a polyamide string that is fixed on either side to the endplate and stuck between two layers (Fig. 4.3(b)). This design is basically a lightweight version of the bow-tie actuator (Section 2.3, [66]). The third version is the same as version two but with an elastic rubber band instead of a polyamide string (Fig. 4.3(c)). This version is the best large-scale copy of the small actuators and the verification of the scaling is based on this design. All of these actuators enable easy handling, independent of external rigid structures. Also, they allow for storage in a half relaxed state and, therefore, have a longer lifetime.
The electrical connection for the large actuators was made with a metal strip along the entire height of the actuator, alternately on the right or left side for counter pole layers.

Figure 4.3: (a) Actuator design with internal reinforcing rods, (b) Actuator design with polyamide string as reinforcement, (c) Actuator design with elastic rubber band as reinforcement.

4.1.3 Agonist-antagonist test-stands

The hinge for agonist-antagonist activation consists of a rigid structure with a DE actuator on each side [100]. When activating one side, the opposite actuator contracts due to the pre-stretch and the hinge deflects. The deflection angle is measured with the hinge fixed vertically on the longer part to reduce inertia effects (Fig.4.4(a)). For the measurement of the blocking moment, the hinge was fixed on the opposite side and its motion blocked by a force gauge (Section 3.1.1, Fig.4.4(b)). In order to

Figure 4.4: (a) Hinge set-up for deflection angle measurements and (b) blocking force measurements. (c) Active hinge [100].
4.1. Scaling of the DE actuators

determine the electro-mechanical properties of the large actuators more easily, a simplified testing configuration was introduced (Fig. 4.5(a)). In the planar test-rig two actuators were placed next to each other, attached to each other in a movable centre-line, and fixed on both ends. Whilst one actuator expands, the other contracts and the centre-line moves to one side. The principle is one of a double push-pull actuator (Section 2.3, [66]). The force of the contracting actuator is similar to that in the hinge configuration, without having additional friction and minimizing inertial forces. From the measured displacement of the centre-line ($\Delta x$), the angle that could be reached with the same actuators in a hinge configuration was determined by simple trigonometry (as described in Section 3.1.1) Figure 4.5(b) and (c) show the test set-up for

![Diagram of Planar Agonist-Antagonist Test Rig](image)

Figure 4.5: (a) Planar agonist-antagonist test rig. (b) Top view of planar test rig: Displacement measurements with laser. (c) Blocking force measurements with force gauge.

The input current and voltage were read directly from the voltage amplifier. Different methods were used to estimate the capacitance. In the first method, dielectric measurements were carried out with an Alpha Analyzer and HVB 1000 high-voltage test interface (Novocontrol) between 0.5 mHz and 1MHz. A direct measurement of the capacitance
of actuators was not possible with the Alpha Analyzer due to its set-up with small copper electrodes. Therefore the pre-stretched ($\lambda_{ps}^x = 3$, $\lambda_{ps}^y = 5$) VHB 4910 dielectric membrane was held between two copper electrodes with a diameter of 25 mm and the relative permittivity calculated from the capacitance. It was found to be approximately 3.1 (at 1 kHz), which is in agreement with [80]. For the actuator we can then determine the capacitance, using for area ($A$) and thickness ($t$) the final geometry after stretching (Eq. 4.6).

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{t} \quad (4.6)$$

The second method calculated the charge $Q$ and thus the capacitance $C$ (Eq. 4.7).

$$C = \frac{Q}{V} = \int i(t) dt \quad (4.7)$$

For the measurement on small actuators, an LCR meter (Agilent type 4263 B) was used to measure the capacitance as a third method. It was not possible to measure the capacitance of large actuators directly; with a measuring frequency of 100 Hz the large actuators could not be fully charged in the available time.

### 4.2 Results and performance

#### 4.2.1 Actuator design

The active strain was measured for the actuator designs with reinforcing polyamide string (Type (b)) and rubber elastic (Type (c)) with varying parameters (Fig. 4.3, and Table 4.4). The results are shown in Figure 4.6. The design with internal reinforcing rods (Type (a)) was not pursued for this size of actuator since the increase in weight is too large and the lifetime is shortened by the actuator-reinforcement interaction. The design with the elastic rubber band showed the most promising performance and is very similar in the design to that of the small actuators, therefore the investigation on the scaling behaviour has been carried out with this design. With a polyamide string as reinforcement, the lifetime of the actuators could be considerably prolonged due to lower strains and stresses in the edges and this design was to be used for the final airship. The parameters of this design (length of the rope for a specific pre-stretch and the pre-stretch itself) have a large influence on
the actuator performance. If the string is chosen too long, too much of the pre-stretch in the y-direction is lost. If it is too short on the other hand a large resistance to the deformation is introduced and too much force is required to strain the actuator. The active strain is therefore reduced again. An optimum has to be found between these two aspects, for maximum performance. An increase of $\lambda_{ps}^y$ from 5 to 6 improves the performance (decrease in thickness) while an increase of $\lambda_{ps}^x$ from 3 to 3.5 resulted in a lower active strain (increase in stiffness). Since the

Table 4.4: Parameters of the various tested actuator designs.

<table>
<thead>
<tr>
<th>Actuator type</th>
<th>No. of layers</th>
<th>$\lambda_{ps}^x$</th>
<th>$\lambda_{ps}^x \times \lambda_{ps}^y$</th>
<th>Dimensions (LxH)</th>
<th>Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type (c)</td>
<td>3</td>
<td>3</td>
<td>3x5</td>
<td>0.25x0.95 m</td>
<td>Elastic rubber band</td>
</tr>
<tr>
<td>Type (b)</td>
<td>3</td>
<td>3.45</td>
<td>3x5</td>
<td>0.25x0.95 m</td>
<td>Polyamide string</td>
</tr>
<tr>
<td>Type (b)</td>
<td>4</td>
<td>3.45</td>
<td>3x6</td>
<td>0.28x0.95 m</td>
<td>Polyamide string</td>
</tr>
<tr>
<td>Type (b)</td>
<td>4</td>
<td>4.1</td>
<td>3.5x6</td>
<td>0.30x0.95 m</td>
<td>Polyamide string</td>
</tr>
<tr>
<td>Type (b)-longer reinf.</td>
<td>4</td>
<td>4.1</td>
<td>3x6</td>
<td>0.27x0.95 m</td>
<td>Polyamide string</td>
</tr>
</tbody>
</table>

Figure 4.6: Comparing the deflection angles of large-scale actuators with varying pre-stretches and reinforcements.
area of dielectric film becomes very large, the probability for defects and therefore failure through electrical break-down is significantly increased. 14 layers (0.75x0.75 m) of dielectric elastomer membrane from different rolls of VHB 4905 and 4910 were tested. The membranes were pre-stretched ($\lambda_x \lambda_y = 3.5 \times 6$ and $4.5 \times 6$) and tested up to 63 V/µm, which is a value far below the theoretical break-down strength. A failure rate due to defects of 14 % was measured. By assuming this to be a material parameter, we can calculate the probability of failure $P(failure)$ as a function of the area with a binomial distribution (Fig. 4.7, Eq. 4.8, with $k = 0$ (no failure), $n=$fraction of the area, $p=$probability for failure=0.14). From these calculations the need for high quality membranes for large-scale applications in general becomes evident immediately. The problem was solved by checking every membrane separately for failure before integrating it as a layer into a complete actuator (see Appendix A).

$$P(failure) = 1 - B(k|p, n) = 1 - \binom{n}{k} \cdot p^k (1-p)^{n-k} \quad (4.8)$$

Figure 4.7: Probability for electrical break-down due to a defect in the dielectric membrane as function of the active area.
4.2.2 Comparison of planar test rig to hinge configuration

The similarity of the two test rigs - the hinge and the planar one - was verified on small actuators. In Fig. 4.8 (a) the maximum deflection angle after 5 s activation is plotted versus the initial electrical field, which is the applied voltage divided by the initial membrane thickness. The results from the hinge are compared with the equivalent angles calculated from the measured strain in a small planar test-stand, both for one- and three-layered actuators. For higher electrical fields and several layers, a difference of the deflection angle of up to approximately 10 % occurs. Fig. 4.8 (b) compares the same actuators in terms of blocking moment, which is made comparable by normalising it with the height and number of layers of the actuator. For the moment differences of up to 37 % were obtained. The actuators were all manually fabricated so the scatter of the production (pre-stretch, etc.) is included and is probably the main reason for the deviation. Force measurements with our test set-up are more prone to error, especially with small planar actuators. This is due to small displacements at fixations or where the force gauge is attached and also due to the asymmetry of the set-up (Fig. 4.9).

4.2.3 Deflection angle

The normalised deflection angle (deflection angle divided by the deflection angle after 5 s activation) is plotted in Fig. 4.10. The designated value is the mean of the measurement results at 2, 2.5, 3 and 4 kV. The three models for time dependency are shown in the same figure (described in Section 4.1.1). Deviations to the experiment may result from the assumption that the stress remains constant and the energy potential changes only with strain which is an approximation. It seems that the Kelvin-Voigt model describes best the behaviour for very short times (< 1 s). The logarithmic fit predicts the behaviour in the entire presented period of time well (< 5 s). The Prony series is a good model for describing the time dependent behaviour at longer times (> 4 s). Fig. 4.11 shows the deflection angle after 5 s activation time versus the initial electrical field. It confirms that the deflection angle does not vary with the size of the actuator. Comparing the large to the small actuator, the deflection angle is very similar. Again, small differences may result from the manual manufacturing process. The Arruda-Boyce model predicts the measurement results well, particularly at lower elec-
Figure 4.8: (a) Comparing the measured deflection angle of the hinge to the calculated deflection angle from the strain measurements on the planar test rig. (b) Comparing the measured blocking moment of the hinge to the calculated moment from the blocking force measurements on the planar test rig.

Figure 4.9: Error source of the force measuring test rig. Small rotations possible due to the asymmetrical set-up (distorted proportions in this figure).

In Fig. 4.12 the deflection angle is shown as a function of the activation frequency. The activation frequency refers to a total cycle (0.1 Hz for example meaning an activation time of 5 s for either actuator). The strain decreases with increasing frequency, which indicates the viscoelastic behaviour of the material.
4.2. Results and performance

Figure 4.10: Deflection angle over time divided by deflection angle at 5 s for large actuators (mean value from various activation voltages). The viscoelasticity is taken into account with the three different approaches.

Figure 4.11: Comparing deflection angle vs. initial electrical field of the large actuator to the small ones (1 and 3 layers). Theoretical approach with Arruda-Boyce model with parameters from Wissler et al. [80].
Figure 4.12: Deflection angle of the large actuator versus activation frequency. The activation frequency refers to a total cycle (0.1 Hz e.g. equals an activation time of 5 s for either actuator).

### 4.2.4 Blocking force

The blocking force was measured parallel to the actuators. Fig. 4.13 shows the force difference between the activated and the passive actuator over time for the large actuators. It would be expected that the force immediately establishes to its full value. The short delay that we see here is mainly due to the test set-up of the planar test-rig, where the fixation to the actuator is slightly elastic. The vibration at the beginning is also an effect of the test-rig. The blocking moment is calculated from the force difference. In Fig. 4.14 the comparison of the maximum blocking moment of a small, one- and three-layered actuator with the large actuator is shown. It is scaled with the size (moment of the large actuator divided by $S$) and number of layers (moment of the three-layered actuators divided by $n$) to be comparable to the one-layered hinge. All three actuators behave in a similar way and show differences of the blocking moment within the range of manufacturing error. Again the Arruda-Boyce model predicts the behaviour well.
4.2. Results and performance

Figure 4.13: Blocking force and blocking moment over time for a large actuator at different activation voltages.

Figure 4.14: Blocking moment (normalised over height and number of layers) versus initial electrical field. Comparing a large actuator to small actuators (1 and 3 layers). Theoretical approach with the Arruda-Boyce model with parameters from Wissler et al. [80].
4.2.5 Sheet resistance of the electrodes

The serial resistance of the electrode ($R$) was calculated from current and voltage measurement $R = V/I$. The measurements resulted in very inconsistent values, varying with temperature, time, activation voltage, mechanical strain and charging history. To isolate some of the effects, measurements were performed on small H-shaped samples of carbon powder rubbed on pre-stretched VHB 4910 ($\lambda_{ps}^x = 3, \lambda_{ps}^y = 5$). Two copper blocks were placed on either side of the centre line and the current between them was measured (Fig. 4.15), the measured area being 10x25 mm ($w \cdot l$). At least five samples were made per test and six measurements per sample. The average specific sheet resistance is the resistivity ($\rho$) divided by the layer thickness ($d$) and can be calculated with the area ($w, l$), voltage ($V$) and current ($I$) (Eq. 4.9).

$$R_s = \frac{\rho}{d} = \frac{V \cdot l}{I \cdot w} \quad (4.9)$$

A first test series was performed to estimate the influence of mechanical strain history on the resistance. The coated membrane was measured, then strained 20 % and measured again after releasing the strain. The specific sheet resistance increased by a factor of 2.58 (Table 4.5). In a second testing series, the coated film was measured, then exposed to 0.5 kV for a few seconds and measured again afterwards. The resistance here

![Figure 4.15: Sheet resistance measurements with H-shaped samples.](image)
increased even by a factor of 3.26. Since these changes are irreversible we might state the hypothesis that the carbon particles rearrange themselves under straining, which would strongly influence the resistance. Also, when applying a high voltage, particles may burn away and thus the resistance increases. It can be seen sometimes that a complete section is burnt away and there is no conductivity left at all (Fig. 4.16). No further experiments were conducted to explain these effects exactly or prove the hypothesis and this could be a matter for further investigations. The scaling was also analysed with an H-shaped sample of five times the area (Table 4.5). The variance of the results for sheet resistance was around ± 30 %. Therefore the 10 % difference in the resistance when scaling the area is negligible and the sheet resistance remains similar for the large area, as predicted by theory. Figure 4.17(a) and (b) show the resistance across the electrode of an actuator when measured directly after building the actuator. The qualitative influence of voltage and mechanical strain can be seen even if the absolute values change considerably in further measurements. The slight decrease in resistance with increasing voltage is reversible and might be due to micro-discharges through air gaps between single particles within the electrode. All of the above explanations for the observed effects are assumptions only and a more detailed study must be carried out for verification.
Figure 4.17: (a) Sheet resistance over activation voltage of the large actuator (first application of voltage, no mechanical straining of the material after electrode application). (b) Sheet resistance over mechanical strain of the large actuator (first application of voltage (30 V), first straining cycle).

Table 4.5: Influence of mechanical loading history, electrical loading history and scaling on the electrode sheet resistance. Measured on H-shaped samples.

<table>
<thead>
<tr>
<th>Description</th>
<th>Measured Resistance ([\text{k}\Omega])</th>
<th>Specific Sheet Resistance ([\text{k}\Omega/\square])</th>
<th>Ratio (increase in (R_s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance after coating (series 1)</td>
<td>67.5</td>
<td>30.6</td>
<td>(R_{s,\text{stretch}}/R_{s,0} = 2.58)</td>
</tr>
<tr>
<td>Resistance after mechanically stretching to 20% strain and releasing again</td>
<td>197.7</td>
<td>79.1</td>
<td></td>
</tr>
<tr>
<td>Resistance after coating (series 2)</td>
<td>62.3</td>
<td>24.9</td>
<td>(R_{s,\text{HV}}/R_{s,0} = 3.26)</td>
</tr>
<tr>
<td>Resistance after applying a voltage of 0.5 kV (at a current of approximately 10 mA) for several seconds</td>
<td>202.8</td>
<td>81.1</td>
<td></td>
</tr>
<tr>
<td>Resistance after coating (series 3)</td>
<td>77.1</td>
<td>30.8</td>
<td>(R_{s,5\text{times}}/R_{s,0} = 1.1)</td>
</tr>
<tr>
<td>Resistance of a sample with 5x the area after coating</td>
<td>69.8</td>
<td>27.9</td>
<td></td>
</tr>
</tbody>
</table>
4.2.6 Electro-mechanical properties

The results of all three methods for measuring the capacitance agreed well (differences of less than 10 %). Calculating the capacitance from a permittivity measurement, from a current measurement or measuring directly with an LCR meter we get for the small one layered actuator: 4.6 nF, 5.1 nF, 5.4 nF; for the small three layered actuator: 13.7 nF, 12.8 nF, 11.8 nF and for the large actuator: 350.7 nF, 353.0 nF. In Table 4.6 the results are shown for the small one-layered planar set-up and for the large actuators. With the scaling factors from Table 4.2 (Section 4.1.1), the theoretical results for the large actuator are calculated from the small one-layered one, using $S = 5$ and $n = 3$. All the measured results are within ± 10 % of the predicted values.
Table 4.6: Scaling the results from the electro-mechanical characterisation of a small one-layered actuator according to theory and comparing them with measured results from a large, three-layered actuator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Estimation based on a small planar one-layer actuator</th>
<th>Results of measurements on the large actuator</th>
<th>Difference predicted vs. measured results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge (of extended act.)</td>
<td>$Q = \int_{t_0}^{t_1} i(t) dt$</td>
<td>$0.0152 \cdot S^2 \cdot n = 1.14mC$</td>
<td>$1.05 \text{ mC}$</td>
<td>-7.9 %</td>
</tr>
<tr>
<td>Capacitance (of extended act.)</td>
<td>$C = Q/V$</td>
<td>$5.1 \cdot S^2 \cdot n = 382nF$</td>
<td>$350 \text{ nF}$</td>
<td>-9 %</td>
</tr>
<tr>
<td>Input Work</td>
<td>$W_{in} = V \cdot \int_{t_0}^{t_1} i(t) dt$</td>
<td>$0.0456 \cdot S^2 \cdot n = 3.42J$</td>
<td>$3.16 \text{ J}$</td>
<td>-7.6 %</td>
</tr>
<tr>
<td>Input Power</td>
<td>$P_{in} = \frac{V}{\int_{t_0}^{t_1} i(t) dt}$</td>
<td>$9.12 \cdot S^2 \cdot n = 0.684W$</td>
<td>$0.631 \text{ W}$</td>
<td>-7.7 %</td>
</tr>
<tr>
<td>Output Work</td>
<td>$W_{out} = \Delta F \cdot \Delta x$</td>
<td>$2.7mJ \cdot S^2 \cdot n = 0.20J$</td>
<td>$0.20 \text{ J}$</td>
<td>0 %</td>
</tr>
<tr>
<td>Output Power</td>
<td>$P_{out} = W_{out}/\Delta t$</td>
<td>$0.040 \text{ W}$</td>
<td>$0.040 \text{ W}$</td>
<td>0 %</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\eta = W_{out}/W_{in}$</td>
<td>$5.8 %$</td>
<td>$6.3 %$</td>
<td>+8.6 %</td>
</tr>
</tbody>
</table>
4.3 Conclusions

Applications with a need for large energy capacitance require DE with large surfaces. Targeting these applications we have studied the influence of size on the performance of the actuators. The parameters for established models in this field have naturally been identified with lab-scale objects. We have now validated the applicability for large-scale (m²-sized) actuators. The experiments show that the large actuators behave in an expected manner and according to theory. In this context we have developed a set-up for the testing of actuators in an agonist-antagonist configuration. Although we could show that the large-scale actuators behave in a similar way to the small ones, much attention must be paid to details in manufacturing and design. Local defects and stress peaks may otherwise lead to problems with regard to reliability and lifetime of the actuators. On the basis of our results we conclude that even larger actuators should behave according to theory. Combining different designs we have built actuators with an active area of 0.75m x 0.95m (at $\lambda_{px}^{ps} = 3.5, \lambda_{py}^{ps} = 6$) (Fig. 4.18, see Appendix A). The reasons why we cannot at the moment produce even larger DE actuators include the limited processing techniques and tools (e.g. the pre-stretching device), and the quality of the dielectric membrane (the probability for defects that might cause electrical or mechanical failure increases with the area. Fail-safe electrodes may present a solution to this problem). Concerning the applicability of these actuators on the biomimetic airship, the following are the most critical points:

- The actuators have to be internally reinforced with carbon rods and polyamide rope, due to the large contraction in the direction perpendicular to the direction of elongation. This leads to an increase in fabrication time, more failure and waste during the fabrication, additional weight and a short lifetime of the actuators due to the stress concentrations.

- The reaction forces of the pre-stretch of the actuators have to be absorbed by the surrounding structure. This leads to additional weight.

- Because the actuators are still a bit adhesive, over time they sometimes stick to the hull and this can cause premature failure of the actuators and even damage the hull.
- The system was constructed for 0.1 Hz actuation. When the frequency is increased, the active strain that we can reach with the actuators and thus the amplitude of the undulation decreases, due to viscoelastic effects.

Additionally, the issue of safety must be considered with large capacities like these. Limitations to our theory for scaling the actuators include thermal effects, electrodynamical effects, and mechanicodynamical effects, such as inertial forces and resonance, which were not considered, but may well play a role at very large scales.

Figure 4.18: Large planar membrane actuators with internal reinforcing carbon rods and polyamide string (0.75 x 0.95 m active area).
Chapter 5

Characterization of alternative DE materials

This Chapter is based on [138].

5.1 Material

The acrylic elastomer material VHB 4910 (by 3M) was introduced by Pelrine et al. in 2000 [59]. In the following years VHB 4910 has been thoroughly investigated as dielectric material, mainly in actuator applications [1, 62, 72] (see Chapter 2.2.1). Today this material is still frequently used due to the achievable electrical fields and active deformation. However it has also some disadvantages. The necessity of pre-stretching the membrane in order to improve the break-down strength and move to a more suitable stiffness range has been confirmed theoretically and in experiment [87, 88, 93]. A large pre-strain of several hundred percent is necessary, which essentially limits the variety of actuator designs. Furthermore, VHB 4910 features a highly viscoelastic behaviour, and the temperature range where it is suitable as dielectric is very limited [139]. These disadvantages influence directly the actuator design (see Chapter 4.3).

Many studies addressing the question of the material choice were limited to conceptual comparisons and estimations in actuator performance from material parameters [7, 59, 69, 84]. An experimental study with a material comparison which is based on a typical application configuration,
such as a linear actuator or a bending device has not been presented. The objective of this characterization is to give a systematic evaluation of two new material systems that have been developed more recently and compare them with VHB 4910 with regard to large-scale applications, such as the biomimetic airship. Both material systems do not require a large pre-stretch and large amounts of raw material is commercially available. The first material - we will call it IPN (Interpenetrating Polymer Network) - was first presented by Yuan et al. [98, 99, 139]. The material consists of a pre-stretched VHB 4910 membrane where the pre-stretch is partially preserved internally by a second, stiffer polymer network made from poly(TMPTMA) under compression. Like pre-stretched VHB, this VHB-poly(TMPTMA) composite material displays a high electrical break-down strength, while it does not require an external structure to maintain the pre-stretch. The second material will be called silicone or corrugated silicone throughout this Section and is produced by PolyPower [107, 140, 141]. It consists of two laminated layers of silicone (Elastosil RT 625, by Wacker). The outer surfaces are corrugated in one direction and sputtered with a thin layer of silver. Since the stiffness of the silver layer is around $10^5$ times that of the silicone, this microstructure introduces a pronounced structural anisotropy on the macroscale. The coated film is therefore much stiffer in one direction and very compliant in the perpendicular, corrugated direction (Fig. 5.1). In this direction the material can be stretched up to 100% approximately without fracturing the silver coating.

The experimental characterization programme is divided into two parts: In the first part (Section 5.2.2-5.2.4) the passive material behaviour is characterized under similar conditions (e.g. environment, measurement methods, strain rates, geometry, boundary conditions, etc.). The second part (Sections 5.2.5, 5.2.6) is dealing with the actuator performance. Conclusions are drawn based on the results gained in part 1 and 2, on their suitability for large-scale applications such as a biomimetic airship. The parameters influencing the performance (deflection angle and blocking moment of the active hinge) and measured in the experiments consequently have been derived from Equation 2.1 (Section 2.1, [69]). Assuming that a device will actuate until purely electrical break-down occurs, the maximum electrostatic pressure $p_{\text{max}}$ depends on the dielectric permittivity $\varepsilon_r$ of the material as well as the square of the true electrical break-down field $E_{BD}$ (Eq. 5.1, with the break-down voltage $V_{BD}$ and
5.2. Experimental characterization

Figure 5.1: (a) Working principle of the corrugated silicone film. (b) Cross-section of silicone film with corrugated surface.

The thickness of the deformed membrane \( t \), Eq. 5.2.

\[
p_{\text{max}} = \varepsilon_0 \cdot \varepsilon_r \cdot E_{\text{BD}}^2
\]  

\[
E_{\text{BD}} = V_{\text{BD}} / t
\]

The maximum active strain \( s_{\text{max}} \) depends on the electrostatic pressure and on the stiffness \( Y \) (Eq. 5.3, \([69]\)). This approach is a simplification and a thorough theoretical description can be found in literature, e.g. \([70, 85]\). On the basis of the experimental results, a calculation of the performance is made and compared with the according activation tests in Section 5.3.

\[
s_{\text{max}} = \frac{1}{Y} \varepsilon_0 \varepsilon_r E_{\text{BD}}^2
\]

5.2 Experimental characterization

5.2.1 Sample preparation

VHB 4910 has been widely used for DE actuators and it has been shown that the largest active strains can be produced at large pre-stretches of \( \lambda_{\text{ps}}^x \) between 2 and 4 in the active direction \([88, 93]\). For our purposes we used a pre-stretch of \( \lambda_{\text{ps}}^x = 3 \) in the active and \( \lambda_{\text{ps}}^y = 5 \) in the perpendicular direction. Dry carbon powder is used for the electrodes.
The IPN is fabricated by spraying a monomer additive TMPTMA onto a pre-stretched VHB membrane \((\lambda_x = \lambda_y = 5)\) and polymerizing it in a vacuum oven \([98,116]\). Upon releasing the membrane from the frame it contracts to a stretch of about \(\lambda_x = \lambda_y = 3\), which is maintained internally by the interpenetrating network under compression. From a thickness measurement in this new reference state, the exact amount of the second component can be determined and with this, the preserved pre-stretch of the material \([81,98]\). All the used membranes for the following investigations were taken from the same batch and an average thickness in the reference state of 67 \(\mu m\) was identified. From this reference state, the material was stretched equibiaxially to \(\lambda_{ps}^x = \lambda_{ps}^y = 1.4\). The electrodes are the same as for the VHB actuators. The corrugated silicone was tested at \(\lambda_{ps}^x = 1.4\), 1.6, and 1.8 pre-stretch in the active direction (4-8 actuators each in preliminary active hinge tests). The largest active deformation was reached with \(\lambda_{ps}^x = 1.4\) (Fig. 5.3(a)). The largest blocking force was produced with \(\lambda_x = 1.8\) (Fig 5.3(b)) but can be scaled with the number of layers and is less critical therefore. The film (made of Elastosil RT 625 by Wacker) is purchased from PolyPower with silver electrodes, which can be removed with a chlorine solution where they are not desired. In Table 5.1 the used pre-stretch factors and original thickness of the materials are listed in an overview with the results of the experimental characterization.
5.2. Experimental characterization

5.2.2 Permittivity

Permittivity measurements were carried out with an LCR meter (Agilent type 4263 B) at 1 kHz. Preliminary measurements with rigid copper-electrodes did not produce consistent results for the corrugated silicone, since the rough surface is either squeezed a lot or air will be trapped between the rigid electrodes. Instead, the membrane was attached to a circular frame with 150 mm inner diameter. The silver electrode of the film was then removed with a chlorine solution leaving a circular area of 28.5 mm in the center. The entire test rig consisting of LCR meter, fixture and frame was grounded in order to reduce external influences. Any outside capacities were compensated by a null balance just before connecting the electrodes to the LCR meter. For comparable measurements with VHB and IPN, sheet-gold electrodes were applied to the adhesive surface with a diameter of 28.5 mm, while the rest of the set-up remained unchanged (Fig. 5.4). For verification purposes, the permittivity of undeformed VHB 4910 (4.75) and silicone (3.1) were measured. While the value for the silicone is in good agreement with data from literature, various values for the permittivity of undeformed VHB have been presented. The permittivity was then measured in the pre-stretched state of the material (see section 5.2.1). Two to four samples were tested for each material, with a maximum deviation of 5%. The mean values are 3.9 for VHB 4910, 3.8 for the IPN, and 2.6 for the silicone (Table 5.1). The difference to the measurements in Section 4.1.3 where a permittivity of 3.1 was determined, lies in the rigid
electrodes that were used. The assumption, that air (or impurities) are included has been mentioned [142, 143], where measurements were made with sputtered gold electrodes. Applying the thick, adhesive VHB film between rigid electrodes without entrapping air has proved difficult and often air enclosures can be seen even by eye. The influence on the measurement result is quite large, even for little air. The measurements in [123] were made with carbon grease electrode, instead of rigid electrodes and the results agree much better with these measurements with sheet gold electrodes.

![Testing set-up for permittivity measurements with sheet gold electrodes.](image)

Figure 5.4: Testing set-up for permittivity measurements with sheet gold electrodes.

### 5.2.3 Electrical break-down field strength

The maximum electrical break-down voltage was measured on the pre-stretched film between rigid brass electrodes of 25 mm diameter with an edge radius of 3.2 mm in order to prevent any fringe effects (Fig. 5.5). We assume the induced failure to be purely electrical due to the rigid electrodes preventing a deformation of the membrane. The voltage was increased with steps of 100 V each second. As a matter of fact, the break-down field is strongly dependent on the stretch state. It is therefore plotted over the inverse thickness, which is varied by stretching the material (Fig. 5.6). The thickness of the film was measured with a precision thickness gauge (MT-30 by Heidenhain). Six different samples were measured for VHB 4910. In order to verify the progression at higher stretches, values from literature (Kofod et al. [87]) were added. Eight or more samples were measured with the other materials. From these results an approximation of the break-down field as a function of the
5.2. Experimental characterization

Figure 5.5: Testing set-up for measuring the break-down field strength.

thickness of the material can be deduced. In Figure 5.6 a function for the dependency of the break-down field of the material thickness (through stretching) is fitted to the measurement data (Eq. 5.4, 5.5, 5.6). This was used for the calculations of a maximum electro-static pressure and maximum active strain in Section 5.3. It can be seen from Figure 5.6 that the break-down field strength increases very much with stretching for the VHB and IPN and is in the same range for both these materials. It also increases for the silicone, but much less and the break-down field strength of the silicone is therefore much lower than that of IPN or VHB. In Table 5.1 the break-down strengths for the pre-stretched states are listed. In the calculations (Section 5.3), the assumption is made that the actuators will expand until the critical electrical field is reached ($E_{BD}$). In reality, the failure mechanism of the actuators may differ from a purely electrical break-down and may occur through electro-mechanical pull-in instability or purely mechanical through a loss of tension in the actuator [71, 75, 144].

\[
E_{BD,VHB} = 2217.2 \cdot t^{-0.7672} \\
E_{BD,IPN} = 4661.5 \cdot t^{-0.9539}
\]
5.2.4 Tensile and relaxation tests

Uniaxial tension tests and relaxation tests were carried out with the three materials in order to gain data with comparable strain rates (10 mm/min (0.00067 s\(^{-1}\)) for uniaxial tests and 500 mm/min (0.33 s\(^{-1}\)) for relaxation tests) and geometry (4x25 mm). Experiments were carried out on a Zwick Z010 tensile testing machine with a 1 N load cell. The tests were performed without electrodes on the VHB and IPN, but with silver electrodes on the silicone film.

The results of the uniaxial tests are shown in Figure 5.7. VHB depicts the lowest stiffness, followed by the silicone, and the IPN displays the highest stiffness. While these tests cause a uniaxial state of stress for IPN and VHB, the transverse deformation of the silicone is constrained due to the large transverse stiffness of the corrugated silver electrode. Experimental investigations have shown, that a pure shear state of stress
results if these membranes are elongated in x-direction [82]. In the actuator configuration, the VHB will be much stretched also in the transverse direction, and a remarkable increase in stiffness may be expected. The same is valid for IPN but to a lower extent, due to the lower external stretch. For the coated silicone film the stiffness decreases where the silver electrode begins to break above 100 % strain.

The isometric relaxation tests (Fig. 5.8) show large differences in the time-dependent behaviour: While the silicone relaxes to about 90 % of its initial force, IPN relaxes to about 55-65 %, strongly dependent on the applied initial stress. After half an hour the VHB is still in the course of relaxing and the initial stress has reduced to about 24-33 %, also depending on the initial stress.

Figure 5.7: Comparing the uniaxial stress-strain behaviour ($\dot{s} = 0.0067/s$).

5.2.5 Isotonic activation tests

Tests were done with planar actuators (50x190 mm, Fig. 5.9), subjected to a constant load. The actuator is fixed with a clamp on top and on the bottom side, a variable weight is attached. This well-known configuration [123] allows for the material to stretch in one direction (x-direction) while the deformation in the transverse direction (y-direction) is small due to the geometry of the sample. During the activation, the voltage was recorded with LabView directly from the high voltage amplifier.
Figure 5.8: Comparing the relaxation behaviour ($\dot{s} = 0.33/s$).

(Trek Inc. model 5/80). The strain was measured with a videoextensometer and also recorded with LabView (National Instruments).

From the isotonic activation tests we can find an optimal pre-stretch for each material in order to maximize the active deformation: At a certain force level we can read out the active deformation of the material by the difference between the activated and the passive curve (Fig. 5.10). The measured results are presented in Figure 5.11 where the tensile force is converted into Cauchy stress, which is plotted versus the stretching factor in the active direction (calculated from the measured displacement). The optimal pre-stretches in the active direction of $\lambda_x = 3$ for VHB and $\lambda_x = 1.4$ for the corrugated silicone seem to be confirmed by these measurements. IPN on the other hand may perform slightly better with a lower pre-stretch of around $\lambda_x = 1.3$ instead of 1.4. Calculations of the optimal pre-stretch will be presented in Section 5.3 and compared to these results. The maximum active strain of each material at the given pre-stretch is listed in Table 5.1.
5.2. Experimental characterization

Figure 5.9: Test set-up and geometrical properties for the tests under a constant load.

Figure 5.10: Tensile force vs. displacement for passive and activated actuator (schematic). From the isotonic tests the pre-stretch can be determined at which the largest active strains can be reached.

5.2.6 Tests on the active hinge configuration

The hinge and test set-up for agonist-antagonist activation is described in Chapter 4.1.2 (Fig. 4.4). It consists of a rigid structure with a pre-stretched DE actuator on each side. When activating one side, the opposite actuator contracts due to the pre-stretch and the hinge deflects.
5. Characterization of alternative DE materials

Figure 5.11: Comparing the isotonic activation behaviour of (a) VHB 4910 (b) IPN and (c) corrugated silicone. (d) shows an overview with all three materials.

**Deflection Angle**

The maximum deflection angles versus applied activation voltage are shown in Figure 5.12 (a). The angles at an activation frequency of 0.1 Hz (activation time of 5 s per actuator) are shown. The largest angles for a given activation voltage were reached with VHB 4910, while about half the deflection angles were obtained with the corrugated silicone and the IPN film. Since all of these materials have a different thickness, the angles were plotted versus the initial electrical field (activation voltage divided by thickness in the pre-stretched state, Fig. 5.12 (b)). It can be denoted that silicone actuators reach higher angles for the same field than IPN. We can conclude that we could get higher deflection angles for a specific activation voltage if the silicone film was produced thinner. The maximum deflection angle that was reached with IPN is limited by the decrease in force of the contracting actuator, which cannot overcome the friction in the hinge any more and therefore a loss of tension in the expanding actuator (visible slacking of the actuator). The failure mode
of the VHB and the silicone hinge on the other hand is assumed to be purely electrical break-down or a local pull-in instability (which of the two cases, was not distinguished, since it is irrelevant for the performance predictions) [71]-[75]. With the silicone a much lower maximum deflection angle is reached due to the lower break-down strength. The time dependent behaviour is shown in Figure 5.13, where the maximum deflection angle is depicted versus frequency. While the achieved deflection angle decreases with VHB and IPN hinges for increasing frequencies, the angle remains unchanged with corrugated silicone actuators. The slight increase towards higher frequencies is due to inertia effects.

![Graphs showing deflection angle vs. applied voltage and initial electrical field.](a) Deflection angle vs. applied voltage. (b) Deflection angle vs. initial electrical field. Comparing VHB, IPN and corrugated silicone at 0.1 Hz.)
5. Characterization of alternative DE materials

Figure 5.13: Deflection angle vs. activation frequency. Comparing VHB, IPN and corrugated silicone at 3 kV activation voltage.

Blocking Moment

The blocking moment is calculated from the measured blocking force \( F_{\text{meas}} \) with \( M = F_{\text{meas}} \cdot L \) and normalized with the height of the hinge \( (m = M/H) \) (Fig. 4.4). Figure 5.14 (a) shows this normalized blocking moment versus the activation voltage. We can scale the blocking moment linearly with the number of layers of the actuators [137]. From the results we can see that approximately two layers of the IPN or three layers of the corrugated silicone film are necessary to reach the same blocking moment as with one layer of the VHB. Figure 5.14 (b) shows the blocking moment per unit height versus the initial electrical field to compensate for the difference in the thickness of the materials. In Figure 5.14 (c) and (d) the work output is calculated, which equals the blocking moment times the deflection angle (see Section 4.1.1).

5.2.7 Discussion

Table 5.1 gives an overview of the obtained results. It can be seen that the permittivity and the break-down strength of the corrugated silicone is lower than that of IPN and VHB. The pre-stretch applied to the VHB 4910 within the IPN network is higher than the pre-stretch applied to the pure VHB 4910 membranes though, which leads to a higher break-down strength of IPN in the pre-stretched configuration. Nevertheless,
5.2. Experimental characterization

Figure 5.14: Blocking force per unit height vs. (a) applied voltage and (b) initial electrical field. Output work vs. (c) applied voltage and (d) initial electrical field. Comparing VHB, IPN and silicone at 0.1 Hz.

The achieved deflection angle at a given voltage or electrical field is higher for VHB than for IPN, which is due to the much higher stiffness of IPN. The stiffness of pre-stretched silicone film is around one third higher (Fig. 5.11) and the permittivity one third lower than that of pre-stretched VHB. This results in a lower deflection angle for a specific electrical field with the silicone hinge. The difference in the achieved angle at a specific activation voltage is even greater due to the larger thickness of the film. The low break-down strength of the silicone results in smaller maximum deflection angles. Above 0.5 Hz, the reduced viscosity of the silicone leads to larger deflection angles with the silicone film than with IPN and above 3 Hz, the angles are even larger than with VHB. This clearly shows the potential of silicones for applications where higher frequencies are needed.
Table 5.1: Summary of some results of the material and actuator characterization.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VHB</th>
<th>IPN</th>
<th>Silicone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial thickness ((T)) [mm]</td>
<td>1</td>
<td>0.067</td>
<td>0.1</td>
</tr>
<tr>
<td>Pre-stretch ((\lambda_x, \lambda_y)) [-]</td>
<td>3.5</td>
<td>1.4, 1.4</td>
<td>1.4, 1</td>
</tr>
<tr>
<td>Permittivity at pre-stretch ((\varepsilon_r)) [-]</td>
<td>3.9</td>
<td>3.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Break-down field at pre-stretch ((E_{BD})) [V/µm]</td>
<td>88.4</td>
<td>160.5</td>
<td>50.1</td>
</tr>
<tr>
<td>Active strain at 3kV, 0.1 Hz (isotonic) ((s)) [%]</td>
<td>21.7</td>
<td>11.1</td>
<td>7.1</td>
</tr>
<tr>
<td>Maximum deflection angle at 3kV, 0.1 Hz ((\varphi)) [°]</td>
<td>14.2</td>
<td>6.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Blocking moment per height at 3kV, 0.1 Hz ((m)) [Nm/m]</td>
<td>0.065</td>
<td>0.040</td>
<td>0.026</td>
</tr>
</tbody>
</table>

5.3 Calculation of actuator performance

In addition to the experimental evaluation, the determined material parameters are subsequently used to predict the actuation performance of actuators made of VHB 4910, IPN, and corrugated silicone film. For high mechanical work, which is requested for many applications, both a certain actuation force and active deformation is required. Since force and deformation depend on the specific configuration and thus boundary conditions, we will calculate the electrostatic pressure in a model situation. The active deformation is further calculated for the constant load and for the agonist-antagonist configuration. For all calculations, incompressibility and dielectric isotropy of the membrane is assumed. The results can be used to compare the different materials and to qualitatively conclude on their applicability in other configurations. A verification of the modelling parameters for IPN and silicone on two more intricate actuator configurations, an isotonic and a hinge configuration, is presented with this (the first verification by Schmidt et al. is done with circular actuators [81,82]).

5.3.1 Electrostatic pressure

Equation 5.1 was used to calculate the equivalent maximum electrostatic pressure \(p_{max}\). The relative dielectric permittivity \(\varepsilon_r\) and the electrical break-down field \(E_{BD}\) depend on the state of deformation (Section 5.2.3, [87]). While the dependence of \(E_{BD}\) on deformation is very pronounced (Fig. 5.6), \(\varepsilon_r\) only changes a few percent within the range of active deformation [87,145]. We will thus subsequently assume a constant value of permittivity throughout the activation. This justifies the use of equation 2.1 instead of the more recently proposed electrostrictive
model (Eq. 2.3, [71]).

The application of a voltage onto the corrugated silver electrode of the silicone film will lead to an electric field vector that is inhomogeneously distributed across the dielectric and that is in general not aligned with the thickness direction of the film. For the specific membrane characterized in this work these effects were investigated into more detail in [82]. With the help of finite element models it was shown that the electric field vector is aligned in z-direction in the major part of the dielectric and deviations occur only in the close proximity of the corrugated electrodes. Also the average normalised value of the electric field vector is very close to the value that is calculated by simply dividing the applied voltage with the film thickness. For a simplified estimation of the electromechanical performance of the silicone membrane it thus seems legitimated to calculate the electrostatic pressure from Equation 2.1.

The electrostatic pressure calculated from Equations 5.1 and 5.2 is given in Figure 5.15 as a function of $\varepsilon_r$ and $E$. The calculation was done for the specific situation of a fully constrained membrane that does not deform under the influence of electrostatic pressure ($\lambda_i = \text{const}$). Further, Figure 5.15 shows the maximum electrostatic pressure of each of the three materials for the specific pre-stretching used for the actuation experiments (Section 5.2.1). As can be seen the low break-down field and permittivity of the silicone leads to a small electrostatic pressure. Comparing the thickness of the pre-stretched VHB and IPN membranes leads to the conclusion that the pre-stretch that is applied to the VHB network enclosed in IPN is higher than the pre-stretch applied to the pure VHB membranes. Hence break-down strength of IPN in the pre-stretched configuration is much higher despite the similar material properties (Fig. 5.6, Table 5.1 and 5.3). This leads to a higher electrostatic pressure on IPN as compared to VHB.

### 5.3.2 Active strain

Active deformations as the consequence of the electrostatic pressure has in literature often be calculated assuming linear elastic behaviour with constant modulus (e.g. [59]). Since all materials investigated in this study reveal a non-linear mechanical behaviour (Fig.5.7) hyperelastic material models are used instead to calculate active deformations. Yeoh (Section 2.1, Eq.2.5) was chosen for the VHB and corrugated silicone, and an Ogden model for IPN (Section 2.1, Eq.2.6). Two different approaches are used because the material parameters for these models are
Characterization of alternative DE materials

Figure 5.15: The maximum possible electro-static pressure for silicone, IPN, and VHB.

the only ones available at this stage for the newer materials. The maximum active strain is dependent on the boundary conditions of the actuator. Since for the corrugated silicone, the anisotropy of the structure inhibits a deformation in the y-direction (Fig. 5.1, \[82\]), we are assuming a constant $\lambda_y$. For a reasonable comparison of all three materials the deformation of IPN and VHB is calculated under the same conditions. This approach is further justified since the height $h$ of the actuators is much larger than their length $l$, and the transverse contraction is therefore small. The parameters for the material models are listed in Table 5.2. For the VHB 4910 the parameters of Wissler \[145\] were used and for the corrugated silicone film and IPN the parameters were established by Schmidt et al. \[81, 82\].

As a first boundary condition, a configuration was chosen, where the external force in the active direction acting on the actuator remains constant (similar to the configuration in Section 5.2.5). From Figure 5.10 we can see that the force in the passive actuator at the pre-stretched state ($F_{\text{passive}}(\lambda_x^{ps})$) is equal to the force in the passive actuator at the activated stretch state ($F_{\text{passive}}(\lambda_x^{a})$) minus the equivalent force developed by the electro-static pressure at the activated stretch-state ($\Delta F(\lambda_x^{a})$). Equation 5.7 shows this force equilibrium for the load per unit height.
Table 5.2: Hyperelastic material parameters.

<table>
<thead>
<tr>
<th>Yeoh parameter</th>
<th>( C_{10} ) [MPa]</th>
<th>( C_{20} ) [MPa]</th>
<th>( C_{30} ) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHB [145]</td>
<td>0.0537433</td>
<td>-0.0004857</td>
<td>3.809e-6</td>
</tr>
<tr>
<td>Silicone(^1) [82]</td>
<td>0.09021</td>
<td>-0.00599</td>
<td>0.00188</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ogden parameter</th>
<th>( \mu_1 ) [MPa]</th>
<th>( \alpha_1 ) [-]</th>
<th>( \mu_2 ) [MPa]</th>
<th>( \alpha_2 ) [-]</th>
<th>( \mu_3 ) [MPa]</th>
<th>( \alpha_3 ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPN(^2) [81]</td>
<td>0.386</td>
<td>0.206</td>
<td>0.119</td>
<td>7.182</td>
<td>-0.066</td>
<td>6.397</td>
</tr>
</tbody>
</table>

\(^1\) with an initial thickness of 100 \( \mu m \)
\(^2\) with an initial thickness of 67 \( \mu m \)

For a given voltage, \( \lambda_z \) and the electrical field \( E \) are functions of \( \lambda^a_x \).

\[
\sigma^p_x(\lambda^ps_x) \cdot t(\lambda^ps_x) = (\sigma^p_x(\lambda^a_x) - p_{el}(\lambda^a_x)) \cdot t(\lambda^a_x) \tag{5.7}
\]

The stress in the passive material can be calculated with [78]:

\[
\sigma^p_x = \lambda_x \frac{\partial W}{\partial \lambda_x} - \lambda_z \frac{\partial W}{\partial \lambda_z} \tag{5.8}
\]

Equation 5.7 can now be numerically solved for \( \lambda^a_x \), and the maximum active strain can be calculated (Fig. 5.16, Table 5.3). Although the maximum electrostatic pressure that was calculated for IPN was much higher than for the other materials, the active strain that can be reached at a certain field is lower due to the higher stiffness of the material. The results from the isotonic tests at 3 kV activation voltage (Section 5.2.5) are designated as points in Figure 5.16. We can see that the models agree well with the measured results. The time dependency is not taken into account in our calculations.

With the same model and for the same boundary conditions, the activation strain is shown versus the pre-stretch and versus the applied (constant) load in Figure 5.17. The calculations are done with a constant voltage of 3 kV. The theoretically optimal pre-stretch can be evaluated and the force which needs to be applied to reach it. The optimal value that we get from the calculation for VHB is at \( \lambda^ps_x = 3.3 \), while for IPN it is \( \lambda^ps_x = 1.2 \), and for the silicone \( \lambda^ps_x = 1.5 \). The optimal pre-stretches evaluated in measurements (Section 5.2.5) are 3.0, 1.3 and 1.4 for VHB, IPN and silicone respectively, not far from the calculated optimum.

In a second case, the boundary conditions of the hinge are applied. Again the stretch in the perpendicular direction is assumed to be constant (\( \lambda_y = const \)), and the material incompressible. The equilibrium of
5. Characterization of alternative DE materials

Figure 5.16: The calculated active strain at a given electrical field for VHB, silicone, and IPN. Boundary conditions as in section 5.2.5. The active strains reached in the isotonic tests are designated with points.

Figure 5.17: (a) Activation strain versus pre-stretch. (b) Activation strain versus applied load.
5.3. Calculation of actuator performance

Table 5.3: Results of the material modelling (calculated).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VHB</th>
<th>IPN</th>
<th>Silicone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Break-down field at maximum active strain ($E_{BD}$) [V/µm]</td>
<td>128</td>
<td>206</td>
<td>54</td>
</tr>
<tr>
<td>Secant modulus over activation period ($Y$) [MPa]</td>
<td>0.303</td>
<td>3.386</td>
<td>0.396</td>
</tr>
<tr>
<td>Maximum electro-static pressure ($p_{el}$) [MPa]</td>
<td>0.56</td>
<td>1.43</td>
<td>0.07</td>
</tr>
<tr>
<td>Maximum active strain ($s$) [%]</td>
<td>62.6</td>
<td>30.2</td>
<td>12.3</td>
</tr>
</tbody>
</table>

forces (load per unit height, Eq. 5.9) in the deflected hinge can then be solved for the stretch-state of the expanded (active) actuator ($\lambda^a_x$) and the active strain and deflection angle can be calculated. $\lambda^c_x$ is the stretch in the contracted actuator, which is equal to two times the pre-stretch ($\lambda^{ps}_x$) minus the stretch in the active actuator (Eq. 5.10).

$$\sigma^c_x(\lambda^c_x) \cdot t(\lambda^c_x) = (\sigma^a_x(\lambda^a_x) - p_{el}(\lambda^a_x)) \cdot t(\lambda^a_x)$$

(5.9)

$$\lambda^c_x = 2\lambda^{ps}_x - \lambda^a_x$$

(5.10)

Figure 5.18 shows the results of the calculated deflection angles. They are compared to the measured results (Section 5.2.6, Fig. 5.12). We can see that the predictions are good concerning the angle for VHB and the silicone but less good for the IPN material. This is due to the fact, that every IPN membrane has a slightly different stiffness based on the manual fabrication process and there are variations even within one membrane [81]. There is also a variance in the fabrication of the hinge system, which leads to an error in the reported measured angles. In general the observations reported in Section 5.2.6 are confirmed. In Table 5.3 a summary of the calculated results is given.

### 5.3.3 Failure

Using the same Equations and material parameters, the electrical voltage was plotted versus the principal stretch in the x-direction. As mentioned in Section 5.2.6, it is difficult to distinguish experimentally between failure through purely electrical break-down or pull-in instability [73, 75, 144]. Zhao and Suo state in [146] that there are three types of dielectrics: Type 1 will break down, before electromechanical instability occurs (Fig. 5.19(a)). Type 2 will fail as the peak is reached, even if that is below the purely electrical break-down voltage, for it will 'jump' to break-down (Fig. 5.19 (b)). Type 3 will be stable again, before break-down and is therefore able to undergo very large deformations at
Figure 5.18: The calculated deflection angle at a given electrical field for VHB, silicone, and IPN compared to the experimental results.

activation (Fig. 5.19 (c)). Lately, ultra-large active strains have been presented with a diaphragm configuration that takes advantage of the instability by jumping to the equilibrium at a higher stretch for the same voltage [146]. Figure 5.20 (a)-(c) displays the results for VHB 4910 in an isotonic configuration with a constant stretch in the non-active direction (y-direction). It can be seen that instability does occur for small pre-stretches in y-direction and for small forces, but that for all cases, electrical break-down will occur before jumping to a higher stretch-state. The curves for electrical break-down ($V_{BD}$) are taken from the measurements in Section 5.2.3. The same results are shown for IPN and silicone in Figure 5.20 (d). With either of these materials, no pull-in instability will occur.

The same calculation was then done for a equibiaxial configuration (Fig. 5.21), where at certain forces, a jump to a higher stretch is actually possible. This configuration is closer to the suggested bubble [146] and the effect may even be stronger, with a force that is not constant, but decreasing with stretch, which is the case in the bubble. A calculation was made for the hinge configuration (Fig. 5.22) for $\lambda_y =$constant$=5$. We
5.4 Conclusions

An acrylic film with an interpenetrating polymer network (IPN), and a corrugated silicone with silver electrodes are compared to VHB 4910. The materials were characterized with the same method and test rigs in order to have comparable values. Permittivity and break-down field were measured, and tension as well as relaxation tests were performed. Actuation performance was investigated under constant load and in an agonist-antagonist hinge configuration. Considering the application for large-scale actuators on a helium-inflated airship, large deflection angles at a given activation voltage and frequency as well as the blocking moment are key performance parameters. Theoretical and experimental results show that the best actuation performance can be achieved with VHB 4910. The situation is changing, when considering the passive behaviour. From the better creep behaviour, a superior performance with regard to achievable design cycles and overall structural efficiency can be expected. The latter is given by the fact that structural reinforcements can see that we cannot reach instability before the contracting actuator is completely relaxed, and that electrical break-down will again occur even before that.

Figure 5.19: A schematic voltage-stretch curve of a dielectric elastomer. Three types of elastomer are introduced in [146], depending on the intersection of the break-down curve ($V_{BD}$) with the voltage curve.
Figure 5.20: Electrical voltage versus principal stretch. Isotonic configuration for various loads, at a constant (a) \( \lambda_y = 2 \), (b) \( \lambda_y = 5 \), (c) \( \lambda_y = 8 \). (d) shows the electrical voltage versus principal stretch for the IPN-modified VHB and for the corrugated silicone in an isotonic configuration for various loads, at a constant \( \lambda_y = 1 \).

and heavy passive support structures can be omitted in the case of IPN and silicone. For active structures with IPN the lifetime is increased because often mechanical failure occurs due to creeping effects around the rigid supporting structure. The reduced viscosity of IPN improves this drastically. For the silicone actuators the lifetime is increased additionally since the low pre-stretch in combination with the low stiffness leads to a reduction of stress peaks at the supporting structures. The predictions for active strain as well as deflection angle are consistent with the strains reached in the isotonic tests, and the measured deflection angles. The specific disadvantages discussed in Chapter 4.3 caused by the dielectric material on the biomimetic airship can be addressed as follows:

- With IPN the internal reinforcements of the actuators would still be necessary, but fewer. With the same amount of reinforcements,
5.4. Conclusions

the stress peaks are much less critical nevertheless. With the silicone the internal reinforcements become unnecessary. This leads to shorter production times and longer lifetimes.

- The forces of the pre-stretch of the actuators are lower in both cases (see also isotonic tests and uniaxial tension test in Section 5.2.4 and 5.2.5). This allows for a lighter inner structure of the airship or for a more stable system.

- Actuators made from IPN are still quite adhesive and can cause damage to the hull therefore. The silicone on the other hand is not adhesive at all. This leads to less failure and it allows for a direct contact between hull and actuator (if the friction between hull and actuator does not diminish the active strain, see also Chapter 6.3).

- The silicone shows very little viscoelastic behaviour and thus the deflection angles remain almost constant with changing frequency (Fig. 5.13). Also with IPN actuators the angle decreases less with increasing frequency than with the VHB. This is important because

Figure 5.21: Electrical voltage versus principal stretch. Equibiaxial isotonnic configuration for various loads.
we can then adjust the undulating frequency independent of the undulating amplitude, as the fish does in a certain range.

An airship with IPN actuators could reach sufficient deflection angles with actuators that would be the same length (Fig. 5.12), but at 4.5 kV instead of 3.5 kV. Different high voltage sources and transistors to switch the high voltage would be needed then, which leads to additional weight. The actuators would have to consist of twice the number of layers or be larger in height to reach the same blocking moment (Fig. 5.14). This is not necessarily a manufacturing problem, but again leads to additional weight. The actuators may still be optimized by using an optimal anisotropic pre-stretch, as it is done with VHB.

To propel the airship with silicone actuators they would have to be twice as long as the existing VHB actuators and three times the number of layers. This leads to a considerable additional weight, some of which may be compensated if the cuts in the hull (to avoid friction between actuator and hull) are not needed (see Chapter 6.3). It is possible that the silver electrodes make this material much more helium tight than the acrylics and a fully integrated solution where the actuators act as
hull at the same time may be a good solution (see Section 3.2).
The acrylic IPN material has been presented before in a stacked configuration [102], where it can fully profit from the fact that it does not need any external pre-stretching structure. The corrugated silicone film may depict a good performance in a similar actuator design as well. In general this material would perform much better, if the break-down strength or dielectric constant could be enhanced. In this context many groups are working with nano-fillers in silicone in order to accomplish this goal, e.g. [91]-[97]. An activation with an amplitude that is independent of the frequency is possible with the silicone. Large-scale applications may profit from the better conductivity of the silver electrodes on the silicone, as well as the lower viscoelastic losses. The main advantages of both alternative materials though lay in the much easier handling and longer lifetimes as compared to VHB. We can conclude that both tested material systems have certain advantages, but always in combination with a lack in other areas. That means that the material will be a compromise and has to be optimized for any particular application.
Chapter 6

Development of an airship with fish-like propulsion

As a proof-of-concept, a biomimetic fish-like model airship was developed with a propulsion based on large membrane actuators. This Chapter is based on [147].

6.1 Theoretical biomimetic considerations

The biomimetic airship is a very interdisciplinary project, uniting aerostatics, fluiddynamics (fish-swimming), ultra-lightweight structural technology, electronics and control, and dielectric elastomer technology in one object. All of these disciplines are highly interactive and changing one parameter may influence several other fields and cause other changes again. Several assumptions and parameters were therefore fixed from the beginning, e.g. the material, the design of the DE, and the shape of the airship. The rainbow trout served as a model, because it is not a specialist in a certain performance aspect (e.g. acceleration or manoeuvrability) but a very versatile swimmer [148]. Some of the interconnections and influences of the different parameters are shown in Figure 6.1. With a given shape, a certain drag force results, and a specific deformation of the body is required to generate a sufficient thrust accordingly. This
deformation was adapted from the trout as well (see Section 6.1.1). This again leads to the required deformation and force of the actuators and thus the size and shape of the active material. That again, together with the given shape gives us the necessary strength of the passive structure and thus the weight of the structure and active material. At the same time, the necessary actuator size and performance leads to a certain necessary amount of batteries, high voltage sources and switches, and therefore to the weight of the electronics. The added masses of all components define the necessary lift that is needed for buoyancy, and thus the volume and size of the airship. In an iteration, the size and weight of the passive structure, active material, and electronics is adapted and the final solution is determined. The presented interconnections show only the rough structure of the designing process. There are many other aspects, such as e.g. the flight velocity, pitching moments, temperature, desired flight time, etc., which influence the final outcome and had to be considered in the course of the development of the biomimetic airship.

Figure 6.1: Evaluation of the necessary size and components of the biomimetic airship.
6.1. Theoretical biomimetic considerations

6.1.1 Discretization of the fish-like motion pattern

For simplicity reasons we decided to use as few bending points or hinges as possible in our airship. Hertel has shown that a propulsion in water is possible with three stiff bodies connected by hinges [19]. From the movement of the rainbow trout [52] a chain of movements with three bending points was generated (Fig. 6.2). For the airship this equals a first joint or hinge within the body and a second hinge between the inflated body and the caudal fin. The last bend in the chain in Fig. 6.2 is assumed to be within the compliant caudal fin itself.

Figure 6.2: Discretisation of the trout movement. Left: Original motion pattern of the rainbow trout. Centre: Discretisation of the motion pattern. Right: Placement of hinges or bending points in the airship. First hinge within the body. Second hinge between the body and the compliant caudal fin [133].

6.1.2 Median and paired fins

All fins other than the caudal fin (e.g. dorsal, anal and pectoral fins) were omitted in our model airship. Many investigations have come to the conclusion that dorsal and anal fins improve the propulsive efficiency and even that they may contribute as much to the thrust as the caudal fin itself [149,150]. In further improved versions, active dorsal and anal fins...
should therefore be included. We did use passive dorsal or anal fin for the flight test with a rigid body (Section 6.2.2). All fish swimming is basically unstable in yaw [149] and yawing of this rigid body led to large drag penalties, which could be prevented somewhat through the extra fins. Active fins may also further improve the performance in this respect. Also, most fishes are slightly hydrostatically unstable. The center of buoyancy being below the center of mass results in a rolling moment at the slightest disturbance, which is also why a dead fish turns upside down [150]. In our case, the center of mass is much lower, due to the gondola with electronics at the keel of the airship (Section 6.3, Fig. 6.11). Some of the fishes balance this rolling moment with a movement of their pectoral fins. Since this is not necessary, we may omit the pectoral fins for our airship. On the other hand preliminary tests with a rigid body and large active pectoral fins (driven by servo motors) have shown greatly improved yaw manoeuvrability (Fig. 6.3). They are also a mean of steering the airship in height and correcting pitching moments, which was not possible with the final model airship. The low center of mass in our final airship led to a periodic rolling, sort of like a pendulum, which could be reduced by having an asymmetric design for the caudal fin, with the lower half of the fin being slightly larger and inducing a periodic counter rolling moment. The reason for omitting any extra fins despite their significant advantages was finally the weight and the insufficient lift of the airship for additional control and energy units.

Figure 6.3: Preliminary fish-like airship with large pectoral fins (driven by servo motors).
6.1.3 Fluid dynamic similarity

In order to translate the locomotion mechanism of a fish into air, the fluid dynamic conditions have to be similar. In general we can say that the following four non-dimensional numbers have to be equal in order to fulfill this requirement:

- Reynolds number (ratio of inertial to viscous forces)
- Mach number (ratio of flight speed to the speed of sound)
- Strouhal number (ratio of forces due to unsteady to forces due to steady flows)
- Froude number (ratio of inertial to gravitational forces)

For our specific case it is sufficient to consider the Reynolds and the Strouhal number. The velocity of an airship is very low and the Mach-number will be negligible (in the order of $10^{-2}$). We can also ignore the gravitational forces and therefore do not need to consider the Froude number. The Reynolds-number (Eq. 6.1) of a trout in steady state swimming is around $0.36 \cdot 10^6$ (L: total length, u: swimming speed, $\nu$: kinematic viscosity). The chosen values for a rainbow trout are taken from Hertel [19]. From the Reynolds-number we can then calculate the velocity that we can expect of our airship with the corresponding length and kinematic viscosity.

$$Re = \frac{u \cdot L}{\nu} = \frac{1.2m/s \cdot 0.3m}{1.002 \cdot 10^{-6}m^2/s} = 0.36 \cdot 10^6 \quad (6.1)$$

The Strouhal number of the trout is calculated to be about 0.45 (f: undulating frequency, $A_{pp}$: peak-to-peak amplitude)(Eq. 6.2) [23]. Again the values for the trout are taken from Hertel [19]. The peak-to-peak amplitude was calculated to be $A_{pp} = 2 \cdot 0.2 \cdot L = 0.12$ m, for Hertel claims that the amplitude of the rainbow trout equals approximately 20% of its total length. From the Strouhal number, the necessary frequency for the airship can be estimated.

$$St = \frac{f \cdot A_{pp}}{u} = \frac{4.5Hz \cdot 0.12m}{1.2m/s} = 0.45 \quad (6.2)$$

Figure 6.4 shows the flight velocity and undulating frequency for airships of various lengths while keeping the Reynolds and the Strouhal number constant (for a kinematic viscosity in air of $\nu_{air} = 16.6 \cdot 10^{-6}$.
m$^2$/s). But while the Strouhal number is reported to have a small optimum range between 0.2\(\leq \text{St} \leq 0.4\) [152], the propulsion may still be possible in a wide range of Reynolds numbers.

6.2 Preliminary wind-tunnel and flight tests

As a first proof-of-concept, in-flight tests were planned with a model airship of 4 m length, driven by a caudal fin with a servo motor. Even before that, the shape and stiffness of the caudal fin and the undulating frequency had to be chosen. For this reason, wind tunnel tests with different caudal fins were done.

6.2.1 Wind tunnel tests with caudal fins

Three different caudal fins were tested in the wind tunnel (Fig. 6.5). Fin A is a simplified model of the caudal fin of the trout. Fin B is still simplified, but longer, such that its length corresponds to the added length of the caudal peduncle and the caudal fin. Both fins A and B are made of expanded polystyrene (Depron). Fin C is short again but of a more fin-like shape and structure. It is made of a framework of
6.2. Preliminary wind-tunnel and flight tests

Figure 6.5: Comparing the three fins that were tested in the wind-tunnel. Fin A and B are made of expanded polystyrene, fin C is made of a carbon framework spanned with a membrane [154].

Carbon rods spanned with a plastic membrane and is therefore very stiff. Although it is built with a bilaminar fin-ray structure [153], the fin-ray was not active. This means that, contrary to the real fish, we do not have an active curvature control of the fin and the fin cannot deflect against hydrodynamic loading. The properties of the three fins are listed in Table 6.1.

Table 6.1: Parameters of the three fins tested in the wind-tunnel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fin A</th>
<th>Fin B</th>
<th>Fin C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>0.3</td>
<td>0.62</td>
<td>0.3</td>
</tr>
<tr>
<td>Height [m]</td>
<td>0.6</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Area [m²]</td>
<td>0.124</td>
<td>0.26</td>
<td>0.12</td>
</tr>
<tr>
<td>Mean Thickness [m]</td>
<td>0.0005</td>
<td>0.009</td>
<td>0.05</td>
</tr>
<tr>
<td>Re₉₅ (with u=1.5 m/s)</td>
<td>28·10³</td>
<td>58·10³</td>
<td>28·10³</td>
</tr>
</tbody>
</table>

In the wind tunnel, the fin was attached to a rigid pole that was able to translate and rotate independently (Fig. 6.6). The translation $t$ is the
6. Development of an airship with fish-like propulsion

Figure 6.6: Scheme of the testing set-up in the wind-tunnel (translational and rotative movement of the fin).

movement that is caused by a rotation of the first hinge, the bending point within the body (Fig. 6.2). Through a rotation of the body, the peduncle of the fin undergoes a translatory movement. The rotatative movement $\varphi$ is the rotation of the fin itself.

The movement of the fin was tracked with a high-speed camera (MotionXtra HG-100K) with 128 fps. The angle was controlled with an angle sensor and the forces and moments were measured with a six-component balance with piezoelectric force sensors (up to $\pm 500$ N with a sensitivity of 48 pC/N). In Figure 6.7 some of the results from the wind-tunnel tests are shown. The coefficient of thrust $c_T$ is calculated as shown in Equation 6.3, with $F_T$ being the measured thrust, $\rho_{\text{air}}$ the density of air, $u$ the wind speed in the tunnel and $A$ the projected area of the fin.

$$c_T = \frac{F_T}{\frac{\rho_{\text{air}}}{2} \cdot u^2 \cdot A} \quad (6.3)$$

Hertel found $72^\circ$ to be the optimal phase shift between the translatory and the rotative movement [19]. All demonstrated results are therefore measured with a phase shift of $72^\circ$. The wind-speed $u$ ranged between
1.45 - 1.70 m/s, the rotative angle of the fin was $\varphi = \pm 40^\circ$ and the amplitude of the translation $t = 223$ mm. Figure 6.7(a) shows the coefficient of thrust of the fin versus the frequency with translation and rotation of the fin. Figure 6.7(b) shows the same result when the fin is only rotated (no translation, $t=0$). The negative results equal a negative thrust and therefore a drag force. From the results we gather that, for these parameters, thrust is generated only above a certain frequency. Unfortunately, the pole where the fin was attached started to shake at higher frequencies, when translating and rotating the fin. We were limited by this to a moderate frequency range, especially for the large fin B. It is therefore difficult to draw final conclusions on whether a translatory motion is useful for speed or efficiency or not. Still, for fin A, no thrust at all was generated without the translatory movement while we did have thrust for higher frequencies with translation. For fin B and C thrust was generated at lower frequencies with translation than with rotation only. In general we can see in both figures that the threshold where thrust is generated is at the lowest frequencies with the very soft fin B. In total, we get a higher thrust with a very stiff fin (fin C) for high frequencies. In Figure 6.7(c) the coefficient of thrust divided by the input power is plotted versus the frequency. This gives us a general idea about the efficiency of each propulsion. Only the positive results are considered, where thrust is actually generated (the negative values are more like a brake-efficiency). From these results we conclude that, although high velocities can be reached with fin C at high frequencies, this requires much energy and is not efficient. Additionally, the weight of a very stiff fin would also be unfavourable compared to the weight of a very flexible fin and therefore unfavourable for the pitching moment of the airship. It was therefore decided to use very soft and large fins for the flight tests, basing on fin B.

### 6.2.2 Flight tests

The proof-of-concept was done with a model airship that was propelled with a flapping caudal fin, while the helium-filled body remained straight (Fig. 6.8). For the body (3 m long), the penguin shape was chosen for its low drag and relatively large volume that allow for enough lift [155]. Again, three different types of caudal fins are tested with, for each type, varying stiffness (Fig. 6.8). The most compliant fin of the series $B_1$ e.g. is called $B_{10}$, the next stiffer one $B_{11}$, etc. Fins of type $B_1$ and $B_2$ are made of expanded polystyrene (Depron) of 3 mm thickness. While
Figure 6.7: Results from the wind tunnel tests. (a) Coefficient of thrust vs. frequency with rotation and translation of the fin. (b) Coefficient of thrust vs. frequency with rotation only. (c) Coefficient of thrust divided by input power vs. frequency. [154]
$B_{11}$ is reinforced with a 3mm-carbon-rod, $B_{21} - B_{24}$ are reinforced with triangular Depron pieces. Fin $B_{30}$ is longer than the others and made of condenser foil (aluminum-polymer composite) with 3mm-carbon-rods. The stiffness is measured by clamping the fin crossways at the root, attaching a weight to the end of the fin and measuring the displacement at the rear edge (Fig 6.9(a)) and in the center of the fin (Fig 6.9(b)). A dorsal fin was used first to impair the airship from too much yawing. Better results were obtained later with a ventral fin which keeps the center of gravity low at the same time and also prevents the rolling motion. The yawing moment was large because a bending of the body was not possible and much of the efficiency is probably lost to this sideways movement (see Section 6.1.2).

In Figure 6.10 the resulting average velocity of the airship (measured over a distance of 10 m) is plotted against the flapping frequency of the caudal fin. From Figure 6.4 we find that for an airship of 3.6 - 4 m, a
frequency of about 0.4 - 0.7 Hz is similar to the steady state swimming of a rainbow trout and we should reach velocities of 1.5 - 1.8 m/s. In the flight tests, lower velocities were reached at these frequencies, but with increasing frequency the velocity increased. Again it seems that the stiffer fins tend to generate the more thrust the higher the frequency, while the velocity generated from more compliant fins does not increase much more, even when increasing the frequency. The thunniform fin seems to be too compliant in general. Since the thunniform fishes tend to swim faster and with higher frequencies but with smaller amplitudes, their fins should be stiffer in order to generate the same thrust [148].

Figure 6.9: Compliance of the fins measured with force introduction at (a) the rear edge, and (b) the center of the fin.
The results also imply that the type $B_1$ and $B_2$ fins were generally a bit too small. Fin $B_{30}$ on the other hand had to be built of very thin foil because it was too heavy otherwise. We learn from these tests that the concept of transferring the fish-locomotion into air is generally possible. It does take a very large, flexible fin to generate the most thrust at low frequencies, while at the same time meeting the ultra-light-weight conditions that a model airship imposes. We decided to build the caudal fin for the final biomimetic airship with design very similar to fin $B_{30}$.

![Figure 6.10: Results of the flight test for the various fins: Velocity vs. frequency.](image)

### 6.3 Overall system of the biomimetic airship

In the iterative process described in Section 6.1 a size of the model airship with a length of 8 m, a height up to 2 m and a maximum width of 1.5 m was determined (Appendix B). From Figure 6.4 we can read out that with a frequency of the oscillation of approximately 0.1 Hz for an airship of this size we should reach velocities of about 0.75 m/s. The airship consists of a rigid inner structure, a helium-inflated hull, a caudal fin, six actuators and a gondola with electronics (Fig. 6.11). It is filled with 11
m³ Helium and can lift approximately 9 kg. Table 6.2 lists the individual components and their weight.

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
<th>Percentage of total weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid internal structure</td>
<td>1690 g</td>
<td>19 %</td>
</tr>
<tr>
<td>Hull membrane</td>
<td>898 g</td>
<td>10 %</td>
</tr>
<tr>
<td>Caudal fin</td>
<td>406 g</td>
<td>5 %</td>
</tr>
<tr>
<td>Actuators fin</td>
<td>395 g</td>
<td>4 %</td>
</tr>
<tr>
<td>Actuators hull</td>
<td>954 g</td>
<td>11 %</td>
</tr>
<tr>
<td>Accumulators</td>
<td>794 g</td>
<td>9 %</td>
</tr>
<tr>
<td>High voltage sources</td>
<td>480 g</td>
<td>5 %</td>
</tr>
<tr>
<td>Control unit</td>
<td>1100 g</td>
<td>12 %</td>
</tr>
<tr>
<td>Wiring</td>
<td>847 g</td>
<td>10 %</td>
</tr>
<tr>
<td>Trim weight/Payload</td>
<td>1350 g</td>
<td>15 %</td>
</tr>
</tbody>
</table>

### 6.3.1 Active elements

From the movement of the rainbow trout (Fig. 6.2), we gather that a first joint or hinge should be at 3.9 m from the tip in the body and a second hinge at 6 m, between the inflated body and the caudal fin. In total there are six planar DE actuators propelling the airship. On the body of the airship there are two equal actuators on each side and two hinges within the inner structure. The actuators are connected though and act as one unit on each side, creating one single bend within the body. The reason why we did not use one single very long actuator on each side of the hull is among others the manufacturing equipment,
which limits the membrane size that we can pre-stretch. Two shorter actuators are attached between the body and the caudal fin in a triangular configuration (Fig. 6.11). The DE actuators for this application are made as described in Chapter 4.2.1 and 4.3. Figure 6.12 shows the actuators attached on the inflated body of the airship and Figure 6.13 shows the actuator moving the caudal fin. The dimensions are shown as it is prepared on the frame ($\lambda_{x}^{ops}=4.1, \lambda_{y}=6$) (Fig. 6.12 (a), Fig. 6.13 (a)), and as it is attached to the airship ($\lambda_{x}^{ps}=3.5, \lambda_{y}^{ps}=6$) (Fig. 6.12 (b), Fig. 6.13 (b)). The pre-stretch creates an asymmetry by stiffening the membrane in the direction where expansion is not required. When cutting the actuators from the production frame, the actuator contract in that direction and some of the pre-stretch is lost.

The active length of each actuator is given by the displacement that is needed at that point. In total the active area of the actuators on the inflated body measures 1.5x0.95 m$^2$ on each side and the actuators are double-layered. The actuators between body and fin are three-layered with an active area of 0.3x0.95 m$^2$. For the actuators the active strain was calculated with simple modelling (described in Section 5.3). From the strain the deflection angles were calculated for the geometries on the hinge or body accordingly (Calculations in Appendix C). Figure 6.14 shows the calculated maximum deflection angles that can be reached as a function of the activation voltage and the frequency (not including friction or external loads, etc.). In the flight tests, the hull actuators were activated with 2.5 kV and the fin actuators with 3 kV with frequencies between 0.1 and 0.25 Hz. We decided to use voltages below the limit of electro-mechanical instability or break-down as a safety factor, thus prolonging the lifetime of the actuators. The hull actuators are more often damaged than the fin actuators because of friction between the hull material and the actuator, and because of the less defined pre-stretch (depending on the internal helium pressure of the hull); therefore, a higher safety factor was chosen for these. From the movement of the rainbow trout (Fig. 6.2) we can derive necessary angles for each joint: 14.6° deflection angle for the hull hinge and 24.9° for the fin hinge. From Figure 6.14 we gather that these angles cannot be reached with the applied voltages, but can theoretically be reached with a voltage of 3.5 kV for the hull actuators and 4 kV for the caudal fin actuators. This leads to a movement of our biomimetic airship that varies from that of the rainbow trout, only about half the amplitudes can be reached, which is probably the main reason for reduced propulsion.
6. Development of an airship with fish-like propulsion

Figure 6.12: Actuators for moving the inflated body of the airship. (a) In an over-prestretched state during production. (b) as it is cut from the production frame and attached to the airship.

6.3.2 Passive structural elements and hull

In the center of the inflated body, an internal rigid structure is attached to the hull membrane. This "backbone" prevents the membrane from assuming a circular cross-section - it creates the fish-like lens-shaped cross-section. There are several reasons for including an internal structure in the airship design:
Figure 6.13: Actuators for moving the caudal fin of the airship. (a) In an over-prestretched state during production. (b) as it is cut from the production frame and attached to the airship.

Figure 6.14: Calculated maximum angles to be reached at various activation voltages and frequencies for the hull- and the fin-actuators.

- Our actuators are attached onto the hull membrane with a pre-stretch in the active direction. The forces for maintaining this pre-stretch are partially absorbed by the membrane stress, which
is built up by the helium pressure in the body. A part of the forces can be transferred to the inner structure though, which turned out to be very helpful for having defined bending-points and keeping a defined shape even when the internal pressure is reduced due to helium leakage.

- The lens-shaped cross-section has a larger lateral area than a circular one, which helps generating thrust.

- With the same absolute active displacement of the actuators, larger deflection angles can be reached (but a larger bending moment is required as well) than with the circular one.

- The keel at the bottom allows us to attach the various electronic components more easily.

The pressure rods in the centre of the structure consist of carbon fibre reinforced epoxy (CFRP) and the keel is made of a CFRP- and GFRP-sandwich-structure. The hull consists of Heptax (by Aeroix), which is a helium-tight membrane that is weldable and weighs 25 g/m². Where the actuators are attached to the hull is constricted to eliminate direct contact between the hull material and the DE actuators (Fig. 6.11(b)). Moving the actuators against the hull membrane leads to friction, constricting the free displacement, and abrasion of the actuators. The fin was made after the model of fin $B_{30}$ in the previous Section 6.2.2; it consists of a Heptax membrane, reinforced with carbon rods, like a fan (Fig. 6.15). The part where the fin is attached to the body is a three-dimensional framework of carbon rods, which absorbs the forces of the pre-stretched fin-actuators and prevents a torsion of the caudal fin. Figure 6.15 shows the final model airship with the attached actuators.

### 6.3.3 Energy supply and control

The electronics are attached in two gondolas at the bottom side of the airship. By its positioning along the length of the airship, the pitching moment can be controlled. The airship is controlled from a ground station. The signals are transmitted by a commercial Wireless-LAN module (WLAN) to the electronic steering device inside the gondola on the airship. For the ground station a commercially available laptop with LabView (by National Instruments) is used. All parameters that are needed for steering the airship (amplitude of the activation voltage for each actuator, frequency, and phase shift between body and caudal fin
6.3. Overall system of the biomimetic airship

Figure 6.15: Final version of the 8 m long model airship driven by dielectric elastomer actuators.

movement) can be chosen on the ground station by the airship operator. The flight parameters can thus be changed on-line during the flight. Turns can be made by activating one side longer than the other. The electronic steering device inside the gondola consists mainly of three parts (see Appendix B):

- Lithium polymer accumulators (LiPo)
- Wireless steering unit and high-voltage supply
- High-voltage switching unit

Due to their high energy density, two LiPo accumulators were used (each 2100mAh 4S1p 14.8V by Kokam). The core part of the flight control unit is the wireless steering unit with an integrated microcontroller (AT-Mega2560 by AVR). It calculates the motion sequences depending on the parameters transmitted from the ground station. The micro-controller is connected directly to the high-voltage (HV) switching unit. To bridge the current peak at the beginning of the charging cycle an electric switching unit was developed which enables us to transfer part of the charge from one DE actuator to the actuator on the opposite
side. With this charging technique it is possible to use smaller HV supply units (Two modules, RA30-6 by Matsusada Precision Inc.) because the high current peak for charging the DE actuator is partly transferred from the activated DE actuator. For switching the high-voltage, ultralight-weight IGBTs (Insulated Gate Bipolar Transistors, IXEL40N400 by IXYS) are used. Eight IGBTs are used in total, two for charging the body actuators (right and left side), two for discharging them and another four for charging and discharging the fin actuators. The IGBT allow for a very dense assembly and therefore a small, light-weight HV switching unit, which is a necessity for using high voltage in lighter-than-air technology. An IGBT driver (Agilent HCPL-3180) is needed to control the IGBT. To insulate the HV (4 kV for driving the DE actuators) from the low-voltage (5 V for controlling the IGBTs), DC/DC converters are used (Econolline REC3). Additionally, different grounds are used for the low-voltage side and for the HV side (see Appendix B for drawings and diagrams).

6.4 Results and performance

The average velocity of the final airship was measured over a distance of 10 m. The airship was accelerated over approximately 4 m before the measuring distance. Keeping the airship going exactly in straight line for the 10 m distance was a challenge; although it is possible to correct the path during flight, this takes some time and may be one reason for the scatter of the measured velocities. The internal helium pressure turned out to be another influencing parameter on the flight performance. Although the internal pressure is very low (around 10 Pa), the membrane stresses and the shape change even with little variations of the pressure. Because the pre-stretch of the actuators in the active (length) direction is maintained by the stress in the membrane, this pre-stretch changes with the internal pressure. A loss of pre-stretch leads to lower active displacement and force of the actuators and therefore a lower amplitude of the body deflection. To minimize this effect, helium was refilled before every test flight. The values depicted in Figure 6.16 give us a good idea of the order of magnitude of the performance of our biomimetic airship. Although the speed seems to increase with frequency, we still have a large variance of the results and it may be too early to draw quantitative conclusions. On the other hand we can see a clear reduction of about 36 % in velocity if only the body or only the caudal fin are acti-
vated. We can show thus that the active body is definitely necessary and contributes to the propulsion. Unfortunately we could not measure the input power during the flight tests and we can therefore not conclude on the efficiency of the different movements.

Figure 6.16: Results of the flight test. Velocity vs. frequency for the propulsion with caudal fin only, with undulating hull only and with both.

6.5 Conclusions

The propulsion of a model airship in a fish-like manner is possible with dielectric elastomer actuators. Although an exact imitation of the movement of a rainbow trout was not possible, the undulation of body and caudal fin was sufficient to create thrust and propel the airship. It was shown that the bending of the body increases the velocity significantly and is a relevant contribution to the propulsion. Another hinge or bending point closer to the tip (e.g. at 1.5 m from the tip) of the airship may decrease the drag further and lead to a better efficiency. One of the advantages of DE actuators over an activation with e.g. servo motors is, that we can achieve a completely continuous bending of the body, as opposed to discreet bending points or hinges, which would probably prove to be an advantage in the fine-tuning of the optimized movement. An active fin ray with suitable compliance may improve the thrust considerably but due to the additional weight at a large distance from the
center of lift may be difficult to implement. Additional active fins (dorsal or pectoral fins) would improve the manoeuvrability and propulsive efficiency.

A velocity of up to 0.45 m/s was reached at a frequency of 0.25 Hz and a phase shift of the undulatory movement between fin and body of 72°. The active strain of the large planar DE actuators did not quite reach their example on the rainbow trout. With a higher activation voltage the required amplitudes could be reached, but proved to be critical for failure and lifetime within the system. But while a different actuator technology may have offered the necessary robustness, the light-weight, softness and possibility to integrate the actuators on the hull make the DE actuators the most attractive alternative. Deflection angles independent of the activation frequency would increase the possibilities for a fish-like motion and lead to faster velocities. A fully integrated solution where the active membrane is at the same time the helium-tight barrier membrane should be aspired.

Further investigations concerning the phase shift and activation frequency are necessary though to optimize the movement. In order to draw a conclusion on the efficiency of this specific propulsion as opposed to a propulsion with a propeller, measurements of the velocities in the wake an calculations of the lost kinetic energy would be necessary. This In general the conclusion could be drawn that the fish-like propulsion may be attractive for small autonomous airships (<3 m) in an application where small velocities are necessary and a noiseless propulsion is desired, such as animal observation, surveillance or filming at a concert.
Chapter 7

Conclusions and outlook

7.1 Main contributions of the present work

In the present work, for the first time, the up-scaling of planar membrane DE actuators is treated thoroughly. In a first phase various designs for the bending activation of an inflated body with planar membrane DE actuators were tested experimentally and analysed. The final version of the body consisted of a rigid back-bone structure with two hinges to allow bending. The inflated body was contracted where the actuators are attached, such that the bending deformation of the pressurized volume was not hindered by friction between the DE actuators and the helium-tight membrane. A fully integrated solution, where the actuators are part of the helium-tight membrane was decided against. Considerations of the scalability and lifetime of the active airship lead to the development of independent actuators that can easily be replaced in the case of malfunctioning or failure. On the final biomimetic airship, multi-layered membrane actuators with a total active area of 7 m$^2$ were attached. Actuators of several m$^2$ active area were built and characterized thoroughly for the first time. The acrylic elastomer VHB 4910 was used as dielectric membrane and a design for large-scale actuators with this specific material was developed. The DE material needs to be pre-stretched biaxially and in the final design this pre-stretch is maintained with internally reinforcing carbon rods and polyamide string. The scaling of the actuators was analysed in theory and then compared with the measured data. An agonist-antagonist hinge (developed by Lochmatter [100]) was used to measure the smaller actuators and a comparable
planar agonist-antagonist test rig was built to measure the large-scale actuators. The results show that this type of actuator scales according to theory. Existing material models with material parameters identified earlier by Wissler et al. [80] for the hyperelastic (Arruda-Boyce) and viscoelastic (Kelvin-Voigt, Prony series [84]) behaviour of the material were applied to the large actuators in an agonist-antagonist configuration and were successfully verified. Electrical properties such as capacity and serial resistance of the electrodes were investigated. Both parameters change with size according to theory. Measuring the serial resistance of dry carbon powder electrodes proved to be challenging. The resistance changes with the stretch of the actuator of course, but also with time and with the application of voltage (several hundred volts) to the actuator. The fast, inhomogeneous, non-stationary transition of charges onto the electrodes and the subsequent electrical current and the influence on the electrodes poses new questions to be resolved in the future. The electrical current is much easier and preciser measurable on large actuators, since it is in the range of a few \( \mu \text{A} \) and needs to be amplified a lot when measuring on small actuators. Also, the electrical current and the serial resistance may well be more important on a large-scale device, if the electrical connections per active area are less it may lead to a slower actuation or heating of the actuator. In general, we can conclude that the actuator design is satisfactory concerning the performance (active strain, blocking force), and the handling of the actuators. Their lifetime is very limited though due to mechanical stress peaks and creeping at the edges of the actuators. However storage with partly relaxed pre-stretch, or at low temperatures can significantly increase their lifetime. Another disadvantage, depending of the application, is that the active strain decreases significantly with increasing actuation frequency due to the large viscoelasticity of the material.

Two alternative materials to the VHB 4910 were tested, a modified VHB with an interpenetrating TMPTMA network [98], and a silicone with corrugated silver electrodes [141]. The three materials were characterized mechanically using the same specimen, test stands and testing parameters. Suspecting that enclosed air may have influenced earlier measurements, the permittivity was measured again with sheet gold electrodes. The break-down field strength is reported over the stretch of the materials and a model is fitted, which was later included in the performance calculations. Finally the performance as actuators (active strain, blocking force) was measured in a test with constant load and on the active hinge configuration. Existing material parameters for hyperelastic ma-
terial models (Yeoh, Ogden) for the newer materials were verified for the first time on more complex actuator configurations (isotonic and hinge configuration). From the calculations the conclusion can be drawn that if the breakdown strength of the silicone could be improved significantly, a very good performance would be possible in the future. While the IPN modified acrylic material features a very high breakdown strength, it is too stiff for displaying large displacements. The experiments show that for many applications the IPN modified acrylic or the silicone material is preferable; the viscoelasticity is reduced drastically, and the lower external pre-stretch improves the entire structural system, since the forces that are introduced are much smaller. The lifetime is improved, since the large pre-stretch often lead to mechanical failure in the VHB 4910. On the other hand, the performance (active strain, blocking force) of the pre-stretched VHB4910 cannot be reached yet with these alternative materials.

A feasibility study and a proof-of-concept was made for a biomimetic airship driven by large-scale DE actuators. By bending the inflated body and a caudal fin sinusoidally with large planar DE membrane actuators, a fish-like movement is created and the airship is propelled through air, similar to a fish through water instead of using propellers. The analysis of the fluiddynamics of the steady-state swimming trout, e.g. the quantification as the characteristic non-dimensional numbers of the Navier-Stokes equation results in a Reynolds number of $0.36 \cdot 10^6$ and a Strouhal number of 0.45. If the airship should be exactly similar to the trout, similarity demands an undulating frequency of 0.1 Hz at a total length of 8 m. The expected equivalent velocity of the airship is 0.75 m/s. A maximum cruising speed of 0.45 m/s was measured with the 8 m biomimetic model airship. The active strain was the limiting factor for a faster speed. Increasing the frequency to 0.2 - 0.5 Hz would have increased the velocity. With increasing frequencies the amplitude of the oscillation decreases though due to the large viscoelasticity, which prohibits a faster speed of the airship. Actuating only body or only tail fin lead to a reduction of 36 % of the velocity. If the airship is up-scaled, the necessary undulating frequency, but also the velocity of the airship decrease to almost zero already at around 10 m length for constant Reynolds and Strouhal numbers. The propulsion is not expected to change much, even with different Reynolds numbers. By allowing lower Strouhal numbers, propulsion is still possible, but presumably with a reduced fluiddynamic efficiency. In general the feasibility of a fish-like airship propulsion based on large DE membrane actuators as artificial
muscles is given.

7.2 Outlook

7.2.1 Material and processing

While the acrylic VHB 4910 displays a good energy density and large active strains, the high viscosity of the material, the large necessary pre-stretch, and the small temperature range where it is usable are drastic drawbacks. The goal is to have a material with the performance of the VHB 4910 (the high break-down strength) and the advantages of the silicones (no pre-stretch, low viscosity, high temperature range). Many new materials have been developed in the past years, with exactly this goal and many have shown promising results for the use as DE actuators or for energy harvesting applications (see Section 2.2.1, 5.1). Mostly the actuator performance was measured on circular actuators of a few cm$^2$ though. For testing new materials for large-scale applications, the manufacturing of large thin homogeneous membranes with little defects is the next challenging step before these materials will be taken up for new designs and applications. A possibility to lower the necessary activation voltage, the fabrication of thinner DE membranes is an option. The handling of such membranes is difficult manually and automated processes (roll-to-roll or the fabrication of multi-layered actuators directly) are necessary. Not many investigations have been done on the lifetime and fatigue behaviour of DE actuators. One reason my also be the lack of automatic processing, since these investigations require statistical analysis and therefore a large number of samples. Lately, a lifetime investigation for stacked actuators has been presented [156], but the topic still leaves a lot of room for further research.

7.2.2 Modelling

Optimization of design is costly and time-consuming, especially for large-scale applications and complex structures. The possibility for easy and concise modelling e.g. with finite element tools is crucial for the introduction of DE actuators in industrial applications. Only few groups have so far started with FEM modelling of complex structures [83,143]. An implementation of an electroactive material with hyperelastic and viscoelastic material parameters may facilitate the step from research
to industrial applications significantly. For improving the efficiency of systems, it may help to include the electronics in the considerations at an early stage, especially for energy harvesting applications.

7.2.3 Characterization and methods

While much is done in the way of characterizing new materials mechanically and as actuators (mostly on small circular actuators or diaphragm actuators), the electrical properties are often neglected. Measuring methods are often challenging for such a soft material, even for thickness measurements or the evaluation of local strain. Additionally, various parameters are depending on the electrical field and/or strain state of the material. Measuring current or capacity is usually done at low alternating electrical fields, which is not representative for the state in an actuator. Also there is no common method for measuring serial resistance over a range of stretches of a soft material. Measuring electrical properties is important on the other hand, especially for large scale DE. Large losses lead to low efficiencies of this type of actuator. While a part comes from viscoelastic losses, mechanical losses of the surrounding structure (such as friction), and losses within the electrical components, a part may be accounted to the large leakage currents. Lately, Di Lillo et al. [142] have found that the leakage current of VHB 4910 at high voltages (3 kV) and stretches ($\lambda_x \times \lambda_y = 5 \times 5$) is in the order of magnitude of the charging current (roughly 70 nA) for an area of 3.14 cm$^2$. Although this is a small value absolutely, for large-scale actuators, it may have a significant influence. More elaborate investigations during the activation and characterization of this parameter on other materials may lead to more efficient systems and designs. The same is true for the serial resistance of the electrodes. It may not always be possible to have the same relative amount of electrical connections onto the electrodes, and a good conductivity is then much more important for large areas. Measurements on the influence of temperature on the electrical parameters and on the performance as actuator have not been presented so far. Moreover, long-term durability and fatigue behaviour are largely unknown.
7.2.4 Biomimetic airship

The fish-like movement was copied from the rainbow trout, but never optimized for the specific shape and features of the airship. An investigation of the efficiency of such an optimized propulsion and the comparison with a conventional drive would be very interesting, looking at the biomimetic aspect of the project. Concentrating on the actuators, a fully integrated active airship where the DE actuators act as artificial muscles and at the same time as helium-tight membrane would be the most elegant solution. For this the actuators must be absolutely fail-safe though and the weight of such a membrane may be too high for model airships. The fluiddynamic simulation of such a large structure with highly instationary flows is difficult and time consuming, but may help in the optimization of the movement of such an airship (such as, how many hinges are necessary, where exactly, stiffness of the tail fin, etc.). The propulsive efficiency and certainly the flight stability may be improved by attaching more fins (pectoral fins, dorsal fins, etc.) to the airship. An improvement is mainly reached, if these fins are active as well. An active fin-ray effect in the caudal fin (a fin that can deform against the hydrodynamic loading through its special controllable compliant structure) should certainly be considered for a next version of a fin-like propulsion in air. The flight instability (rolling mostly) may also be eliminated with an intelligent control instead of more fins.

7.2.5 Applications

Observation and surveillance platforms are one field where an airship with completely noiseless propulsion is attractive. Animal observation, filming of events where noise is disturbing (such as concerts e.g.) are examples where hovering is required and a silent airship is much more efficient than a helicopter. Airships have further been considered for stratospheric platforms. While the fish-like propulsion is not necessarily required for such an application, DE actuators as means of triggering deployable structures e.g. may be interesting, being soft and adaptable in structure and light weight at the same time. The same sort of application could be imagined for satellite structures. While the required forces are small in space, large deformations may be needed and weight is a crucial factor once more. Active damping of these ultra-large systems may be required. Architecture, art, and building technologies are further fields, where a deformation of entire walls, roofs or surfaces can
have an impressive visual effect, but may also divide a hall into different rooms changing at actuation, or adapt to changes in climate or wind. In a more technical sense, the adaptation of the shape of any inflated or compliant structure could be acquired with DE actuators. An example is a morphing wing with planar actuators to deform the profile and angle of attack, or even a deformation of the whole shape of a hybrid airship to improve the aerodynamic properties.

Comparably large DE structures of a few m\(^2\) have so far mainly been produced for energy harvesting applications [129]. Large capacities are needed for energy harvesting and thus large stacks or large membranes (depending on the surrounding structure and exact application) are necessary. Harvesting energy from ocean waves or wind (e.g. with an energy harvesting flag) are therefore large potential fields of application for large-scale membrane dielectric elastomers [157].
Appendix A

Actuator fabrication process

A pre-stretching device was developed where membranes of 1 m$^2$ with a pre-stretch of $\lambda_x = \lambda_y = 6$ at a maximum could be produced (Fig.A.1). Material and pre-stretch can be changed easily on this device and it can be used for stretching as well as relaxing films.

Figure A.1: Manual pre-stretching device for large membranes.
Fabrication of a three-layered actuator:

- Pre-stretch two VHB 4910 membranes onto two fabrication frames.
- Apply electrodes on both sides.
- Attach electrical leads (tin-coated copper tape by 3M).
- Test both membranes up to 3 kV.
- Pre-stretch a VHB 4905 membrane onto each of the VHB 4910 layer (roll on with a soft roller to avoid air-bubbles).
- Apply the frame made of carbonfiber reinforced epoxy (CFRP) plates and polyamide-string on one of the membranes. For the actuators on the body, the reinforcing frame consists additionally of carbonfiber-epoxy tubes with 2mm diameter, which are insulated and made adhesive by wrapping them with VHB 9473. Between the carbon tubes and the polyamide-string, a disk of polyvinylchloride (25 mmm diameter, see Fig. A.2) reduces the local stress peaks.
- The membrane is reinforced by adding triangles of VHB 9473 at the edges, so that the risk of tearing at these stress-peaks is reduced later, when cutting the actuator from the frame. The string is attached to the membrane with strips of VHB 9473.
- Add the two frames together (roll on with a soft roller to avoid air-enclosures). There is now a sandwich of electrode-VHB 4910-electrode-VHB 4905-Reinforcement-VHB 4905-electrode-VHB 4010-electrode.
- Test the whole configuration.
- The CFRP-plates are attached through holes with Velcro strips around the fabrication frame.
- The actuator is cut from the fabrication frame and held in position by the fabrication frame in one direction and by the reinforcing polyamide string in the other direction (where it contracts slightly due to the pre-stretch).
- The pre-stretch in the active direction can be reduced by loosening the Velcro strips for storage of the actuators.
For two-layered actuators, the same procedure is applied, but only one frame is used, the first VHB 4905 membrane is added, then the reinforcement and then the second layer of VHB 4905. Ketjen Black EC600-JD by Akzo Nobel is rubbed onto the membranes with a foamed soft rubber (by Maagtechnic) (Fig. A.3). A mask is applied to avoid carbon powder in unwanted areas.

![Figure A.2: Detail of the reinforcing framework of the actuators on the airship body.](image1)

![Figure A.3: Loose carbon powder electrodes rubbed onto VHB 4910.](image2)
Appendix B

Drawings and Diagrams

B.1 CAD drawings

The design of the passive structure was done in collaboration with Aeroix, and it was built by Aeroix (Fig. B.1). The electronics are carried in two gondolas on the keel of the airship. The first gondola contains the wireless steering unit with an integrated microcontroller (ATMega2560 by AVR) and two high-voltage amplifiers (RA30-6 by Matsusada Precision Inc.) (Fig. B.2). It calculates the motion sequences depending on the parameters transmitted from the ground station. The micro-controller is connected directly to the high-voltage switching unit (Fig. B.3).

B.2 Electronic diagrams

The control unit was developed by Christian Dürager. These diagrams are his work, and are added here for the integrity of the document.
Figure B.1: Side view of the passive structure in the biomimetic airship.
Figure B.2: High voltage supply and wireless steering unit.
Figure B.3: High voltage switching unit.
Figure B.4: Diagram of the electronics of the biomimetic 8m model airship.
Figure B.5: Diagram of the control unit for the actuators on the biomimetic 8m model airship.
Appendix C

Trigonometry of the hinge

For small deflection angles and for hinges with a large length-to-width ratio, the deflection angle was approximated with \( \varphi = \arcsin\left(\frac{2\Delta x}{W}\right) = \arcsin\left(\frac{\Delta L}{W}\right) \) (Section 3.1.1). The general trigonometrical relations are shown here (Fig. C.1 [158]).

Figure C.1: Geometry of an active hinge structure.
\[
x_1 = T_2 \cdot \cos(90^\circ - \varphi) \quad \text{(C.1)}
\]
\[
x_2 = \frac{W_2}{2} \cdot \cos(\varphi) \quad \text{(C.2)}
\]
\[
x_3 = x_1 + x_2 - \frac{W_1}{2} \quad \text{(C.3)}
\]
\[
x_4 = x_1 - x_2 - \frac{W_1}{2} \quad \text{(C.4)}
\]
\[
y_1 = T_2 \cdot \sin(90^\circ - \varphi) \quad \text{(C.5)}
\]
\[
y_2 = \frac{W_2}{2} \cdot \sin(\varphi) \quad \text{(C.6)}
\]
\[
y_3 = T_1 + y_1 - y_2 \quad \text{(C.7)}
\]
\[
y_4 = T_1 + y_1 + y_2 \quad \text{(C.8)}
\]
\[
\beta_1 = \tan^{-1}\left(\frac{x_4}{y_4}\right) \quad \text{(C.9)}
\]
\[
\beta_2 = \tan^{-1}\left(\frac{x_3}{y_3}\right) \quad \text{(C.10)}
\]
\[
L_1 = \frac{y_4}{\cos(\beta_1)} \quad \text{(C.11)}
\]
\[
L_2 = \frac{y_3}{\cos(\beta_2)} \quad \text{(C.12)}
\]
\[
\text{(C.13)}
\]
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