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Body segment of an active airship based on dielectric elastomers

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ABSTRACT

Many attempts have been made to mimic the movement of a fish in water, for their propulsion is very efficient and can be optimized for various parameters such as e.g. speed, acceleration or manoeuvrability. Conventional airships are driven by propellers, which is efficient, but only in a small range of application. The goal is therefore to copy the fish-like movement in air. Dielectric electro-active polymer actuators (EAP) are used to bend the airship body because of their light weight, because of the large deformations they can achieve and because a large-scale planar application is possible. The manufacturing and characterization of one bending airship body segment with planar dielectric elastomer actuators is described in this paper. In an experimental study, several designs for the combination of EAP actuator with airship hull were evaluated qualitatively and quantitatively. From these preliminary results a conclusion shall be drawn, which design to use in the final active airship.

Keywords: Biomimetics, Airship, Actuator, Electro-active polymer, Dielectric elastomer

1. INTRODUCTION

Lighter-Than-Air vehicles have come back into attention with new applications such as transportation of heavy cargo, stratospheric platforms, but also surveillance or animal observation [1-4]. Classical propulsion systems composed of piston engines with gears and propellers show a good efficiency only in a small range of application (e.g. a limited range of rotational speed, etc.). In addition these systems are noisy and, if driven by piston engine, have a negative impact on the environment by pollution. The idea is to apply on a model airship the propulsion system of a fish [5] which is very efficient over a wide range of applications and can be optimized for various parameters such as e.g. speed, acceleration or manoeuvrability.

The goal is to prove the biomimetic propulsion of a fish in air and to improve our knowledge on large planar DE by developing an indoor model airship of 6 m that can move at a speed of 1 m/s [6]. It has been shown with the similarity theorem that at a frequency of 0.2 Hz the Strouhal number of the airship is equal to the Strouhal number of a rainbow trout [7]. The concept has also been proven experimentally with a flapping tail fin on a 3 m blimp [8]. Also looking at the movement of a rainbow trout at steady swimming [9], a local strain of 15 % was calculated. When the continuous motion is simulated by four rigid parts with three hinges, the deflection angle of the body segment nearest to the head accounts to 15 °.

In order to bend the inflatable body of an airship in a fish-like manner, soft planar light-weight actuators that can achieve large deformations are needed. In this project, dielectric elastomers (DE) are used for the actuation [10, 11]. The compliant capacitors consist of VHB 4910 as dielectric material, coated with carbon black particles as electrodes. When activated with high voltage the electrodes attract each other, the dielectric is squeezed in thickness direction and expands in planar direction. The membrane DE actuators are attached on both sides of the airship to the gastight envelope in an agonist-antagonist configuration. Since we need a contraction as well as expansion, they are applied under a prestrain which can be maintained e.g. by the internal pressure. Then the DE are activated alternately and bend the inflated body, just as the muscles do in a fish (**Fig. 1**).

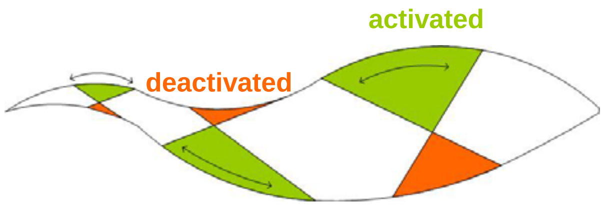

Fig. 1: Agonist-antagonist principle on an airship

2. EXPERIMENTS

2-1. Bending Body Segment without envelope

In small square sample, the composition of envelope material and DE was tested and the interaction was evaluated (**Fig. 2**) [6]. In order to exclude the unfavourable effects discovered in this testing series, such as friction, a functional model was built where the DE are arranged in the final configuration but supported by a mechanical 'ribcage' structure instead of internal pressure (**Fig. 3**). The ribcage consists of an aluminium framework of 1 m length, 0.5 m height and 0.225 m wide, with hinges in the center to make it bendable. Attached are bent 2 mm carbon rods of which the internal four can rotate freely to allow the elongation of the actuator and the outermost are fixed to transmit forces onto the aluminium frame. The active area consists of five fields of 310 x 70 mm and is attached with a prestrain of 500 % (circumferential direction) and 250 % (longitudinal direction).

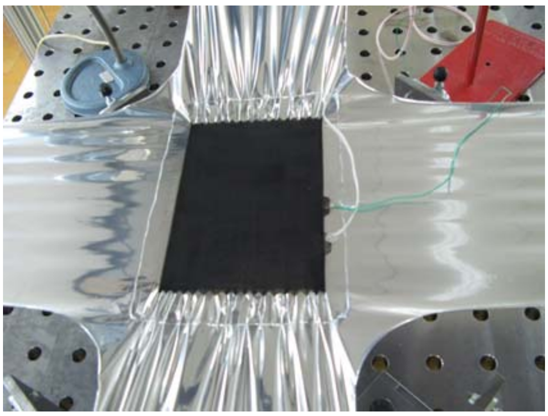

Fig. 2: Testing of material combination DE (black) and gastight envelope material

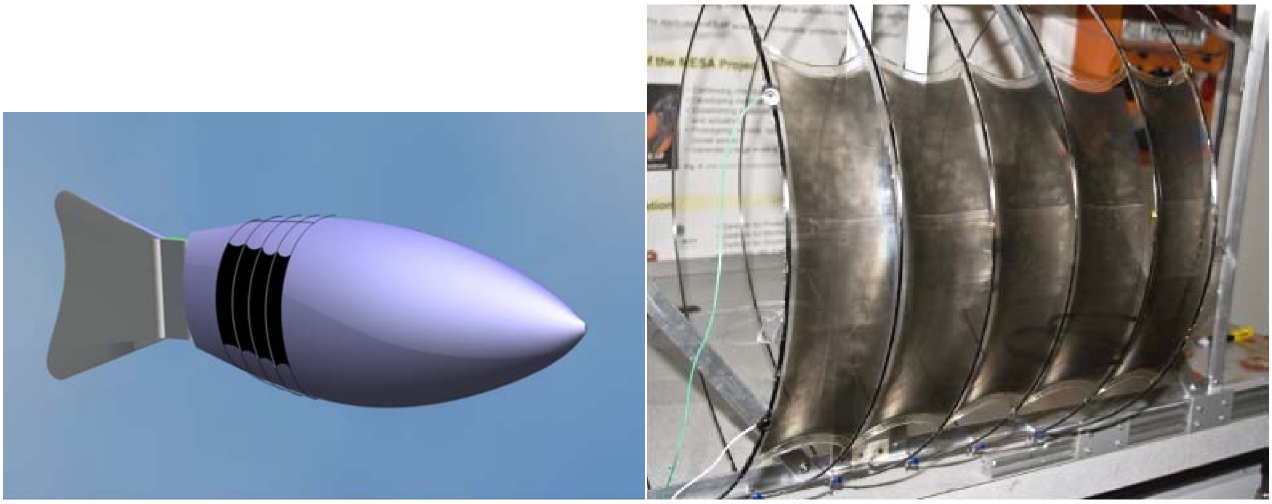

Fig. 3: Bending body segment without envelope ('ribcage' segment)

The measurements were done at various frequencies (0.2 Hz, 0.5 Hz, 1 Hz) with various activation voltages (3.5 kV, 4 kV, 4.5 kV). A one-layer and a two-layer actuator are tested. The measured parameters are deflection angle, force, current and voltage.

2-2. Inflatable Bending Body Segment

In a second testing series, an inflatable airship envelope segment was activated. It consists of an internal framework in the middle plane with hinges in the center and an inflatable envelope. The rigid inner structure is equal in size to the one described in section 2.1 but is made of carbon and aluminium tubes. To minimize unfavourable influences of the envelope on the actuator, the shape is narrowed around the hinge area in order to decrease the contact between DE and gastight material (Fig. 4).

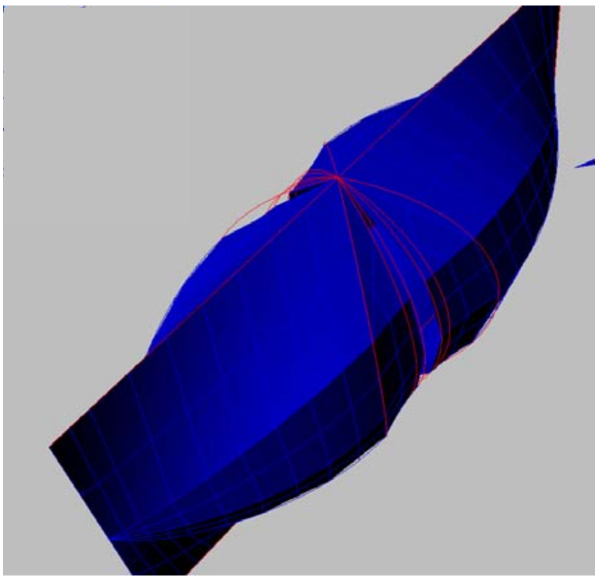

Fig. 4: Design of the passive inflatable envelope

The actuator design was adapted in such a way that it is independent of the internal pressure in circumferential direction. The prestrain in that direction is maintained by internal reinforcing rods (Fig. 5). The active area is 330 mm times 176 mm and the prestrain again 500 % (circumferential) times 250 % (longitudinal).

Fig. 5: Actuator design with internal reinforcement

Again, the measurements were done at various frequencies (0.2 Hz, 0.5 Hz, 1 Hz) with various activation voltages (2 kV, 2.5 kV, 3 kV). The measured parameters are angle, force and input power (current, voltage). In some cases strain was measured with a videoextensometer, either directly on the body segment or on the planar actuator. Also the internal pressure was monitored for some measurements.

The tested actuators are listed in Table 1. Several numbers of layers were tested. An actuator with less area but more layers was compared to others with more area but fewer layers. The weight was recorded including fixation and wiring which account for around 10 g, depending on cable length, etc. The serial resistivity was measured in several places on the electrode and varied between 5-10 kΩ/cm.

Table 1: Actuator test matrix

Act. No.	No. of layers	Height	Weight
1.1	1	176 mm	
1.2	1	176 mm	26.9 g
3.1	2	176 mm	38.6 g
3.2	2	176 mm	35.9 g
4.1	2	88 mm	21.0 g
5.1	3	176 mm	38.4 g

3. RESULTS

3-1. Results - Body Segment without envelope

The one layer actuator on the 'ribcage' segment showed deflection angles up to 12.8 ° at a frequency of 0.2 Hz and with an activation voltage of 4 kV (**Fig. 6**). There is a rapid decrease in deflection with an increase in frequency. 1.1 Hz is the resonance frequency of the system, which explains the increase of the deflection at 1 Hz. At 4 kV the actuator seems to reach its maximum charge density within 2.5s (0.2 Hz), therefore the deflection angle cannot be increased by applying higher voltages. This can also be concluded when looking at the result of a static force measurement at 0°: raising the voltage from 4 to 4.5 kV has no significant influence on the force (**Fig. 7**).

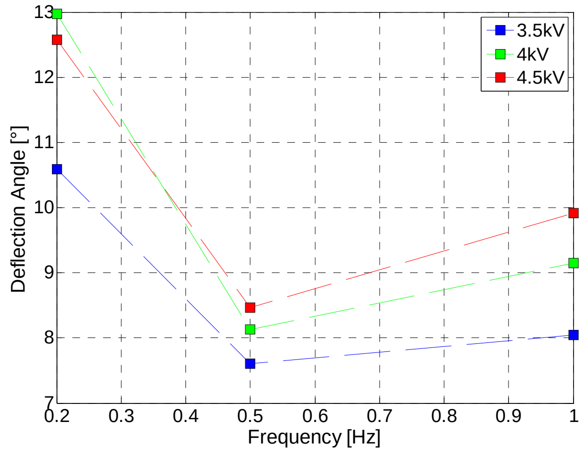

Fig. 6: Deflection angle vs. activation frequency

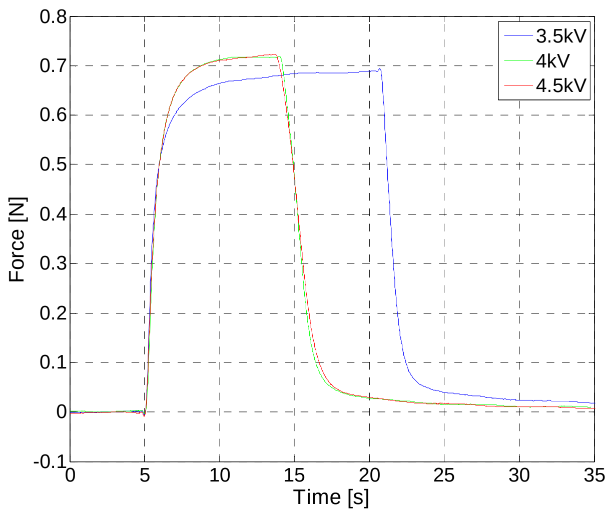

Fig. 7: Force measurement at various activation voltages

The two-layer actuator could be deflected to a maximum angle of 11° at 4 kV and 0.2 Hz (**Fig. 8**). Again the full charge density seems to be reached at 4 kV and the angle cannot be increased with higher voltage. The deflections are slightly smaller than in the one-layer actuator. The force was measured again with a force load cell and we reach about twice the force of a one layered actuator (**Fig. 9**). The force can be converted to a moment and results in 0.7 Nm at 4 kV for two layers and 0.36

Nm for one layer.

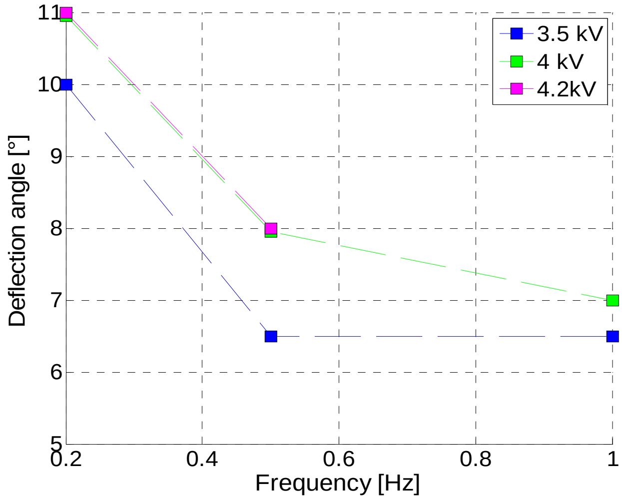

Fig. 8: Deflection angle vs. frequency, 2-layer actuator

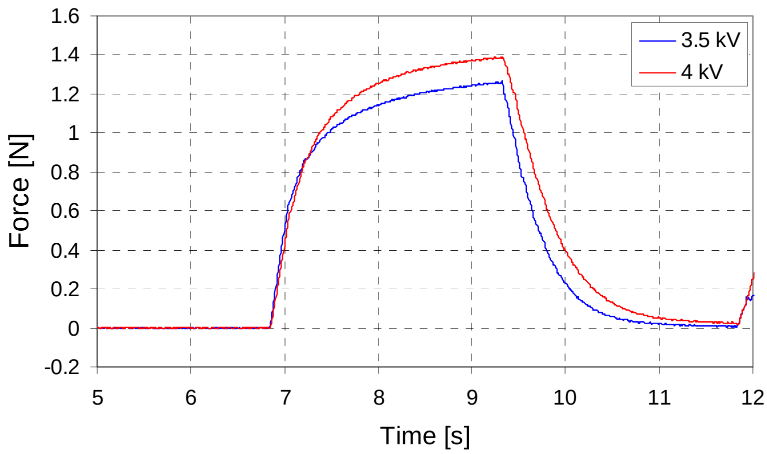

Fig. 9: Force measurements at 0°, 2-layer actuator

3-2. Results - Body Segment without envelope

The angle measurements of several actuators show, that an increase in the number of layers will lead to an increase of the deflection angle (**Fig. 10**). Looking at the results in Section 3.1 this was not to be expected. Here the actuator was partially directly pressed onto the inflated envelope and could not expand well through friction effects. Therefore several layers help to overcome these dissipative forces and lead to better results.

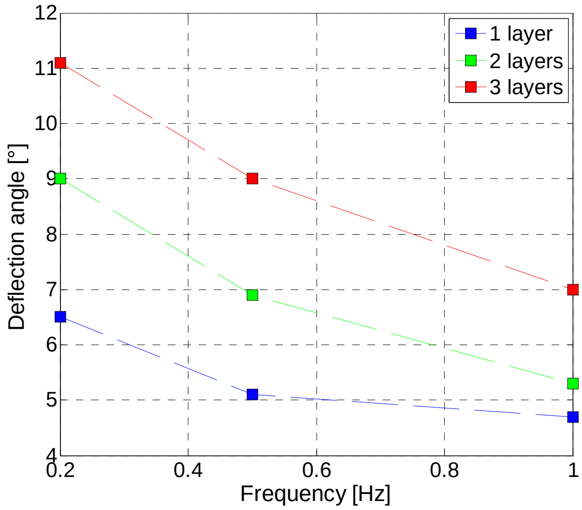

Fig. 10: Comparison several layers, 3kV, actuators 1.2, 3.2, 5.1

In order to find out whether it would help to have less area to decrease friction but more layers to retain the force, an actuator was built with half the height of the others (88 mm) but two layers. When building the smaller actuators though, instability occurs and the internal reinforcing rods tend to tilt to one side (**Fig. 11**). This phenomenon depends on the length to height ratio of the actuator; it was found that a ratio of slightly less than 2 is sufficient for temporarily stable actuators (up to 3 days at least). The actuator was therefore fixed to the inflated segment at half its length.

If compared to the one layer actuator with a height of 176 mm it can be seen that we have no improvement of the deflection (**Fig. 12**). The slight decrease of the angle cannot be explained by the variation of the geometry but rather by the normal variation between actuators and by a slight instability problem of the reinforcement rods that could not be overcome even with the fixation.

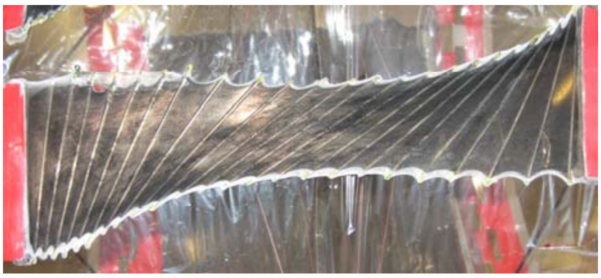

Fig. 11: Instability of the reinforcing rods.

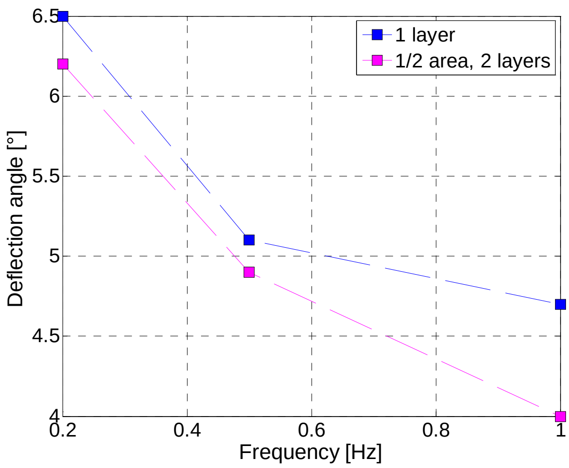

Fig. 12: Comparison of small 2-layers and large 1-layer actuators (actuators 1.2, 4.1)

The dependency of the deflection angle of the internal pressure in the body segment is plotted in **Fig. 13** for a 2-layer actuator. It can be concluded that a minimum internal pressure is necessary in order to maintain the prestrain of the actuators in the direction of the strain. Too much pressure does not have a negative impact on the deflection which has been the case in preliminary tests and can be avoided with the appropriate design of this body segment.

Force measurements were carried out with a load cell that was attached to the internal structure at the end of the body segment. The force difference was measured at several angles at an activation frequency of 0.2 Hz (**Fig. 14**). The one layered actuator was attached to a previous model of the body segment and therefore is quantitatively not comparable to the other actuators. It shows qualitatively a very similar behaviour though. From two to three layers the force increases more than linearly which has been observed before in other planar applications [12, 13].

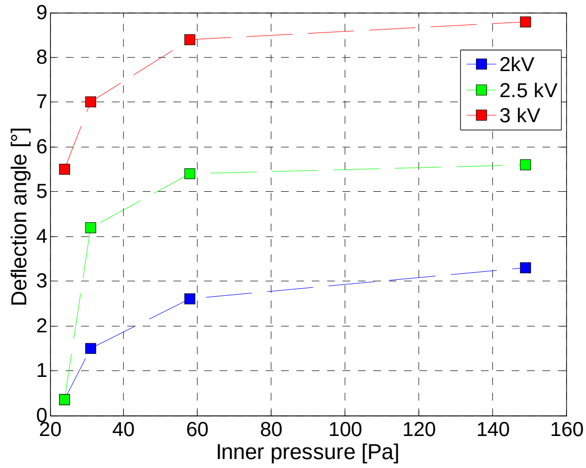

Fig. 13: Influence of internal pressure, actuator 3.2, 0.2 Hz

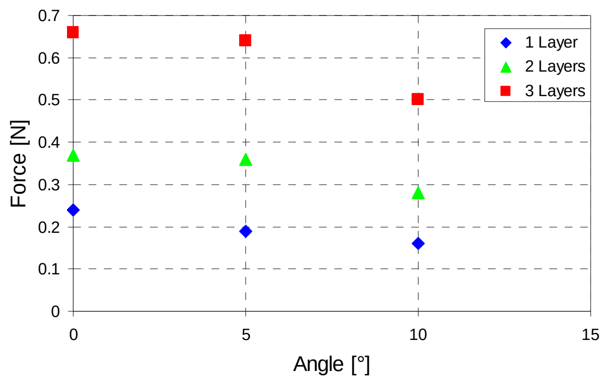

Fig. 14: Static force at various angles, actuators 1.1, 3.2, 5.1

3-3. Efficiency

For our agonist-antagonist system the force-displacement curve for two actuators is schematically shown in Fig. 15. For the small area that our actuators work in, linear-elastic behaviour is assumed as a first approach. The hatched area represents the work output for our system. The displacement is calculated from the measured angle as follows:

$$\Delta L = b \cdot \tan(\frac{\alpha}{2}) \quad (1)$$

b = Total width of the body segment.
ΔL = Prolongation necessary to achieve the deflection angle α. ΔL = L2-L1 = L1-L0.

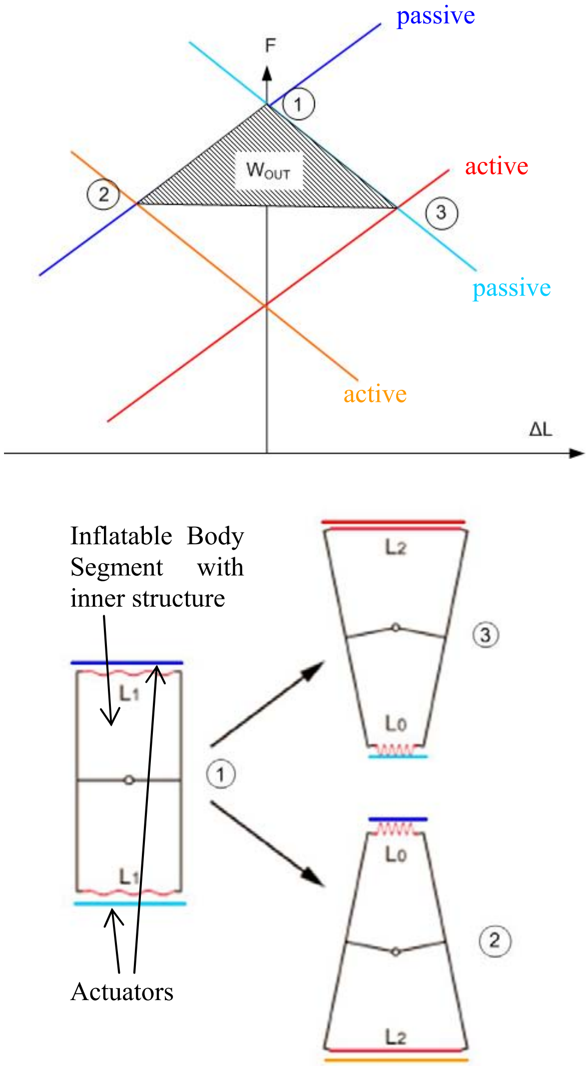

Fig. 15: Schematic force-displacement curves for two actuators if we assume them to be linear-elastic.

For the input work calculation the area under the current curve was taken and multiplied with the (constant) voltage. The calculation of the output work is described in Chapter 2. Efficiency is calculated by dividing output work through input work. An efficiency of approximately 4 % was calculated for a four-layer actuator on the inflated body segment. The detailed results are shown in Table 2.

Table 2: Efficiency consideration

	‚Ribcage' Segment	Inflatable segment
Number of Layers	2	4
Active Area [m]	0.22	0.24
Activation Voltage [kV]	4	3
Current Limitation [mA]	3	18
Charge [mC]	0.5	0.26
Electrical Work [J]	2.0	0.79
Average Input Power [W]	0.8	0.32
Max. Input Power [W]	10.83	54.08
Deflection Angle [°]	21.6	19.6
Strain [%]	22.8	21.2
Displacement [m]	0.09	0.07
Force Difference [N]	1.38	0.49
Output Work [mJ]	117	34
Output Power [mW]	47	13.6
Specific Output Power [W/m^2]	0.09	0.06
Efficiency	5.87%	4.25%

4. CONCLUSION AND OUTLOOK

With this preliminary study, the specified deflection angle of 15° could not be reached until now. Both active body segments reach angles above 10 ° at 0.2 Hz though: The 'ribcage' segment 12.8° at 4kV with one layer and the inflated body segment 11° at 3 kV and three layers. While we assume to have reached a saturation of electrical charge in the first body segment, an increase of the voltage is possible for the second one. Since the electrostatic pressure increases with U^2, 3.5 kV should theoretically lead to the desired 15° deflection:

$$\frac{15}{11} = (\frac{x}{3})^2 \rightarrow x = 3.5kV \qquad (2)$$

The results may be improved if the area or the length of the actuator is increased. Friction between actuator and airship envelope material has a negative impact on the deflection and can be partially overcome by adding several layers to the actuator. More tests with 4-5 layers should be carried out on the inflatable segment. Without the effect of friction, several layers do not improve the deflection of the segment, therefore separating actuator and envelope instead of adding several layers is another possibility to achieve larger deflection angles. Buoyancy is a very critical factor in a model airship and the solution that will lead to less additional weight will have to be chosen. With an improved fabrication process the reproducibility (prestrain, etc) could be guaranteed and thus the performance of the actuators improved. The scaling to the large airship may have a positive effect on the performance (friction, boundary effects, etc). In the coming months a full-scale active airship will be designed and manufactured and these aspects may be examined experimentally.

Moreover it can be concluded that a minimum internal pressure must be guaranteed while too much internal pressure has no negative influence on the deflection angle with the current design of the passive segment structure.

Even if the exact continuous motion of the rainbow trout cannot be mimicked, propulsion of the airship with discrete hinges will still be possible. Bending the body even with smaller angles might still reduce the drag coefficient as opposed to a completely stiff body with a flapping tail fin.

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