

Design of a morphing winglet trailing edge with fluid actuation - Design process and experimental results

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Abstract. Integrating active control surface technology into aircraft wings with confined spaces is challenging. It would be beneficial to do so to enable more efficient wing designs for e.g. load alleviation. This paper details a winglet trailing edge surface composed of fluid actuated morphing unit structures (FAMoUS) that enable control surface deflections under the corresponding aerodynamic hinge moments.

The design of the FAMoUS actuators is comprised of elastomer and metallic stiffeners, which under internal pressure from a fluid exert displacement and force and thus output work. Combining these unit structures in a bimorph setup a trailing edge control surface is built, which is structural and actuating part at the same time.

The structural dimensioning of a demonstrator with 1 m span-width is shown, based on a finite element analyses consisting of detailed tuned material parameters obtained from testing on the individual unit structure tests as well as the inclusion of hydrostatic fluid elements to determine effective stiffnesses from the pressure-volume relationship between the housing structure and internal fluid.

The process of choosing a suitable actuating system including the feedback control and hydraulic systems is presented.

Finally experimental results of tests are presented, starting with calibration of the feedback system with an external measurement, also clarifying deflection uniformity along the span of the demonstrator. Deflection performance and deflection rate are discussed and compared with the predictions from the finite element analyses. The findings are discussed and contextualized. A summary of the results is given and an outlook on the way forward is presented.

Key words: Morphing winglet, Hydraulic systems, Flight Control

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1 Introduction

1.1 FAMoUS Principle

The design of the morphing winglet trailing edge is based on fluid actuated morphing unit structures. Those unit-structures are comprised of a combination of an elastomer with aluminium stiffening material enclosing a pressure cell. Increasing the pressure of such a cell is resulting in an elongation of the orthotropic part as shown in figure 1. Combining two unit-structures in a bimorph configuration lead to a bending movement which is the setup used for the trailing edge. The pressure change in the cavity of can either be done by pneumatic or hydraulic means and previous works have shown that this fluid actuated morphing unit structures can fulfill deflection and stiffness requirements [1, 2].

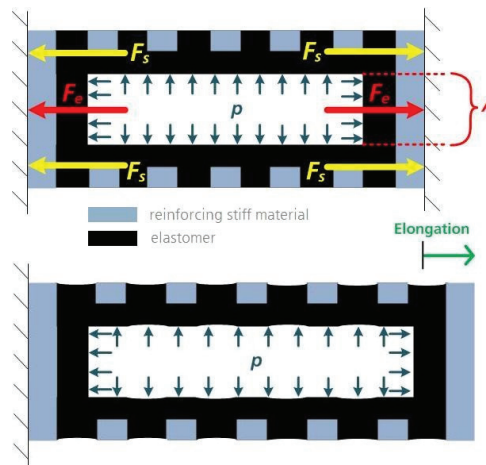


Figure 1: Principle of pressure cells

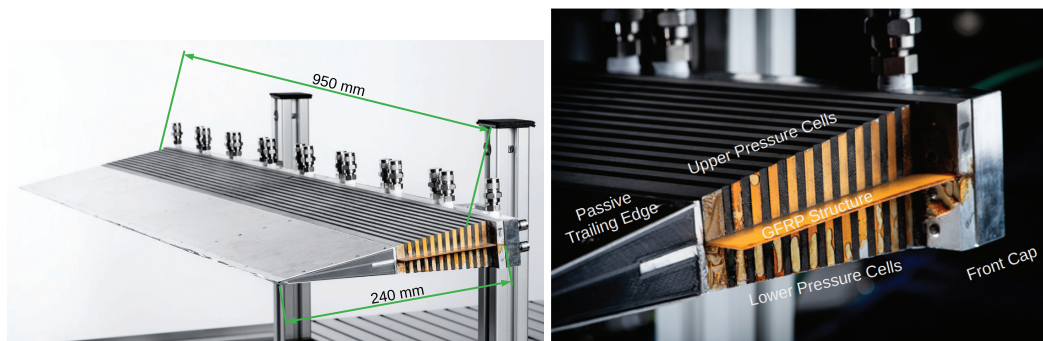
1.2 Morphing Winglet Trailing Edge Demonstrator

A winglet reduces drag but increases load on the wing. In order to reduce the weight a load reduction is desirable. Active load reduction can be achieved with a winglet tab, i.e. a control surface at the trailing edge of the winglet. A morphing structure, being a control-surface with a continuous deflection, promises to have higher change in lift for a given deflection angle than a conventional control surface according to [3, 4] which together with the confined space at the winglet motivates building a demonstrator for a morphing winglet tab using the FAMoUS principle.

The goal for this demonstrator is to raise technology readiness level to TRL 3. In table 1 some requirements for the design are listed. The demonstrator is designed to have a spanwise dimension of nearly 1 m (as shown in figure 2) and is also taking into account the system design to actuate it.

Table 1: Requirements for trailing edge

Function	1st Priority		2nd Priority
	High Speed Performance	Maneuver Load Alleviation	Gust Load Alleviation
Deflection Range	$\pm 10^\circ$	$\pm 15^\circ$	$\pm 15^\circ$
Deflection Speed	$10^\circ/\text{s}$	$20^\circ/\text{s}$	$80^\circ/\text{s}$
Position Accuracy	$\pm 0.1^\circ$ Rationale: Ensure device position compliant with aerodynamic tolerance		
Design Assumption	Either 2 actuators or 1 actuator and damper Rationale: Avoiding flutter in case of failure		

**Figure 2:** Structural part of demonstrator

2 Design and Manufacturing

2.1 Structural Design

For the structural design a standard aviation aluminium AL7505 combined with an ethylene propylene diene monomer rubber (EPDM) AA6CFZ from Kraiburg is chosen. The bimorph structure is further complemented with an glas-fibre reinforced plastic (GFRP) structure placed in the neutral axes to enforce bending without elongation of the trailing edge. The final setup can be seen in the right of figure 2.

In order to predict performance with a finite element calculation, previous tests are used to tune the hyperelastic material model describing the EPDM as reported in [5, 6]. In order to reduce overall weight not the whole length of the winglet tab is pressurized. In figure 3 results are shown predicting 11° deflection at 14 bar differential pressure between upper and lower pressure cells which equals $0.79^\circ/\text{bar}$ deflection.

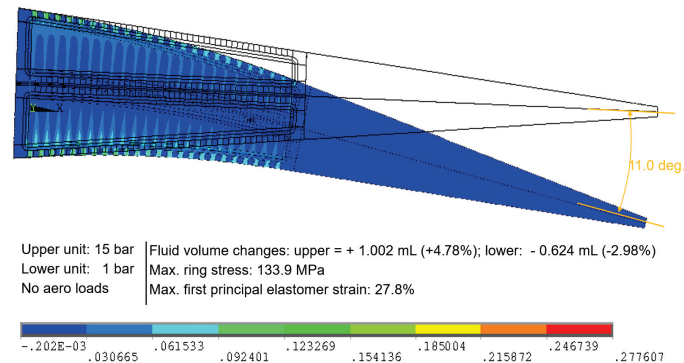


Figure 3: FE Result, color indicating strain in EPDM

2.2 Manufacturing

Manufacturing the 1 m demonstrator is done by building 8 subassemblies individually, i.e. 4 upper and 4 lower pressure cell parts, and combine them later to the full length structural part as shown in figure 4. The steps for manufacturing are:

- Manufacturing aluminium parts of 4 mm thickness with all cutouts
- Stack aluminium parts with EPDM and vulcanised
- Assemble upper and lower pressure cells and mill EPDM from the cavities
- Combine upper and lower cells with GFRP sheet (figure 4 right hand side)
- Mill outer shape of demonstrator

Some prototype parts expose leaking, leading to integration of EPDM-bladders as shown in left side of figure 5 to ensure leak tightness of the pressurized cells. The finished morphing part of the demonstrator is depicted in figure 5 with the pressurized cavities indicated as active while the other cavities are marked as passive.

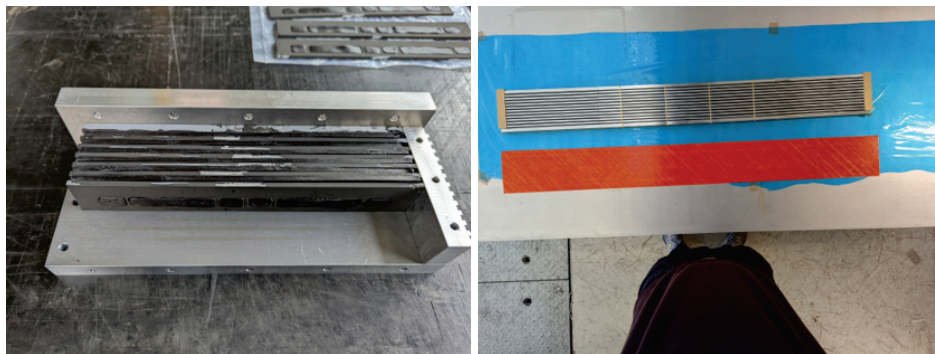


Figure 4: Manufacturing



Figure 5: Left: EPDM-bladders for leak tightness, Right: Active and passive cavities

2.3 System Design

The pressure cells can in principle be driven by pneumatic or hydraulic systems. For the 1 m demonstrator a hydraulic system is chosen as elucidated in [7]. The design and dimensioning of this hydraulic system is discussed in [8]. The setup used in the demonstrator is based on a electro hydrostatic actuator (EHA) as shown on the left side of figure 7. Central to this system is a bidirectional pump driven by an electric motor which is moving fluid volume between upper and lower pressure cells thus establishing a differential pressure. A second pump ensures that all pressure cells are at least pressured to 3 bar through the check valves connected to the line depicted in green. Relieve valves connected to the red line bleed pressure exceeding 17 bar back to the tank. Due to the non-linear elastic behavior of the EPDM structure, sensors must be used that enable the direct measurement of the deflection angle for position control. These sensors are alternatively based on strain-gages or fibre-bragg grating based as shown in figure 6.

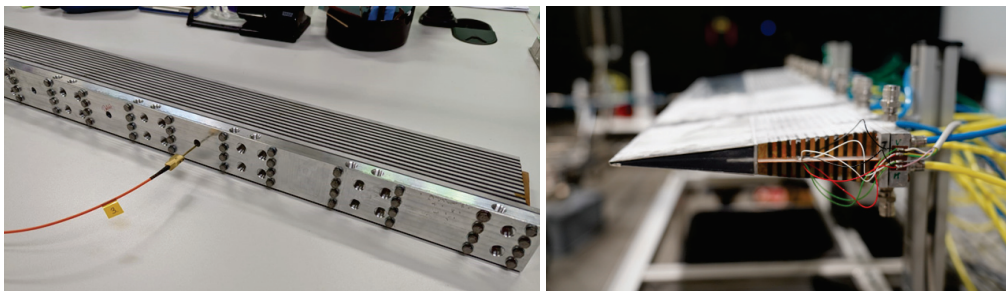


Figure 6: Feedback sensors (Left: Fibre-bragg sensor, Right: Strain-gage)

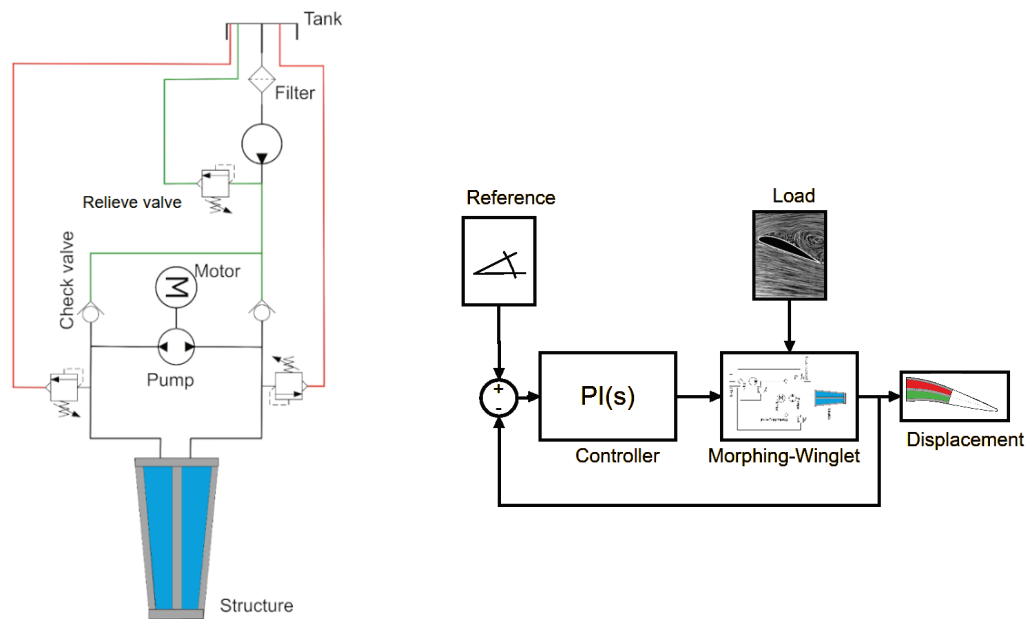


Figure 7: System architecture (Left: Electro hydrostatic actuator, Right: Control-loop)

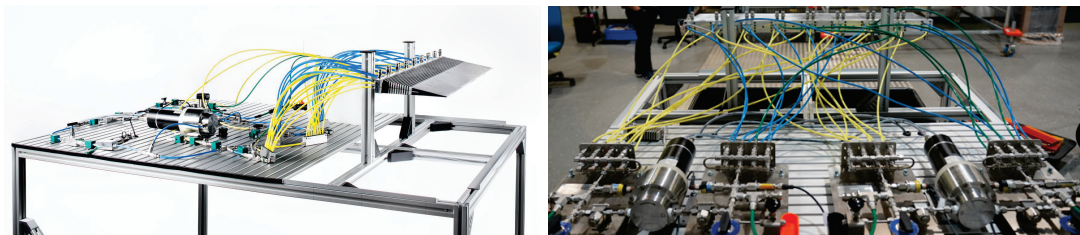


Figure 8: Demonstrator (Left: Single EHA system, Right: Second EHA system for redundancy)

3 Experimental Data

The experiments are designed to achieve multiple goals:

1. Calibration of the feedback sensors, to ensure position control is based on correct angles of deflection.
2. Verification of the design model.
3. Showing that assumption of the actuation being a one degree of freedom system is correct. As the system architecture is designed to have just one control value (i.e the differential pressure between upper and lower pressure cells), the whole demonstrator is supposed to have uniform deflection.
4. Measuring performance of the demonstrator regarding speed and accuracy according to

requirements (see table 1).

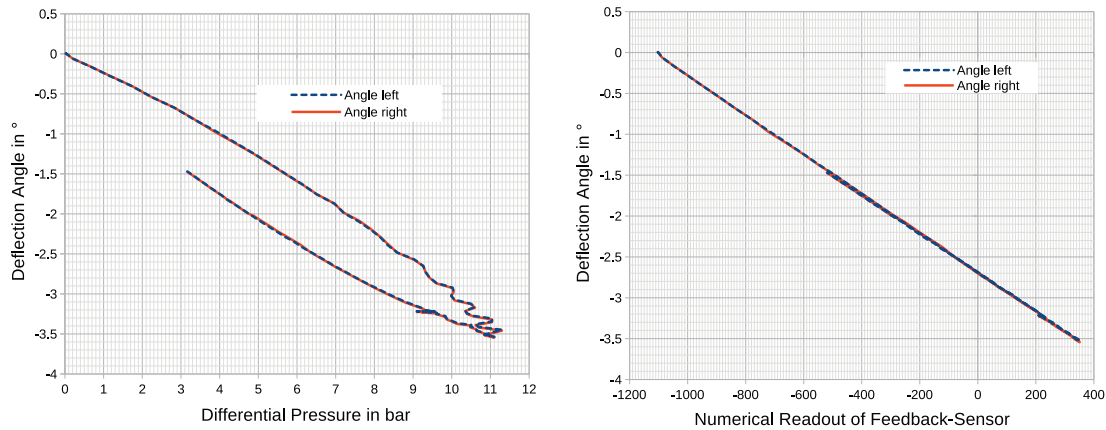


Figure 9: Measured Displacement (Left: Angle over Pressure, Right: Angle over Raw Sensor Readout)

A photogrammetry system is used to externally measure displacements of the demonstrator. Two cordwise cuts along the demonstrator are evaluated for the deflection angle.

The externally measured displacement angle versus the differential pressure of upper and lower pressure cells is shown on the left side of figure 9, clearly showing the non-linearity between pressure and displacement caused by the EPDM material. The right hand side of the figure displays displacement angle versus measured values of the internal sensor, exhibiting linear correlation between both signals. This measurement is used to calibrate the control loop.

In both plots of figure 9 the two externally measured displacements are identical, indicating that the morphing tab is deflecting uniformly, thus supporting the assumption of just needing one control value.

As it is mentioned in section 2.1 the finite element model predicted $0.79^\circ/\text{bar}$ deflection rate. Looking into figure 9 we see a deflection of 3.5° at 11 bar which corresponds to $0.32^\circ/\text{bar}$, which is just 40% of the predicted value. Looking into the discrepancies two causes are found:

1. Looking at the left side of figure 5 bladders are shown that ensure leak-tightness. These bladders decrease the cross section of the pressure cells, so that the force is reduced 30%. Taking this into account the measured value is 58% of the calculated.
2. Looking on the right side of figure 5 the active and passive parts are shown. Due to problems with manufacturing the ratio between active and passive parts is changed from 46.4% as calculated to 27% as build. Correcting the calculation with this aspect the measured value reaches 95% of the prediction. This is deemed to be a sufficiently accurate prediction to validate the used model.

In order to test for accuracy of the system, the trailing edge is loaded and unloaded with an added weight; the resulting deflection over time is given in figure 10 on the left side for open-loop condition, on the right side for closed loop control. As can be seen the accuracy of $\pm 0.1^\circ$ is reached for the closed loop setup.

The deflection speed is evaluated to be about the order of magnitude required for high-speed performance but inadequate for maneuver load alleviation or gust alleviation as shown on the left side of figure 11. That seems to be caused by the driver for the electric pump not actually delivering the needed current and thus torque for shifting the fluid volume between the pressure cells (see right hand side of figure 11).

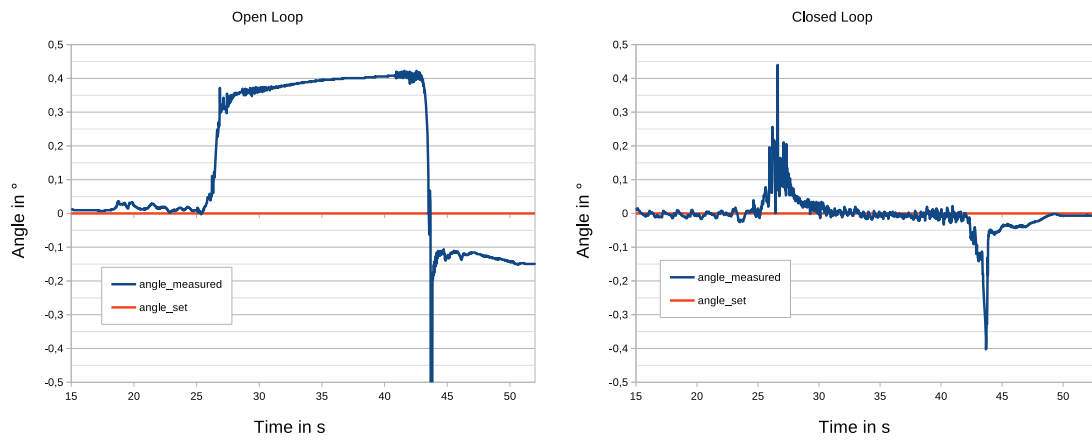


Figure 10: Accuracy of displacement with Disturbance (Left: Open loop, Right: Closed loop)

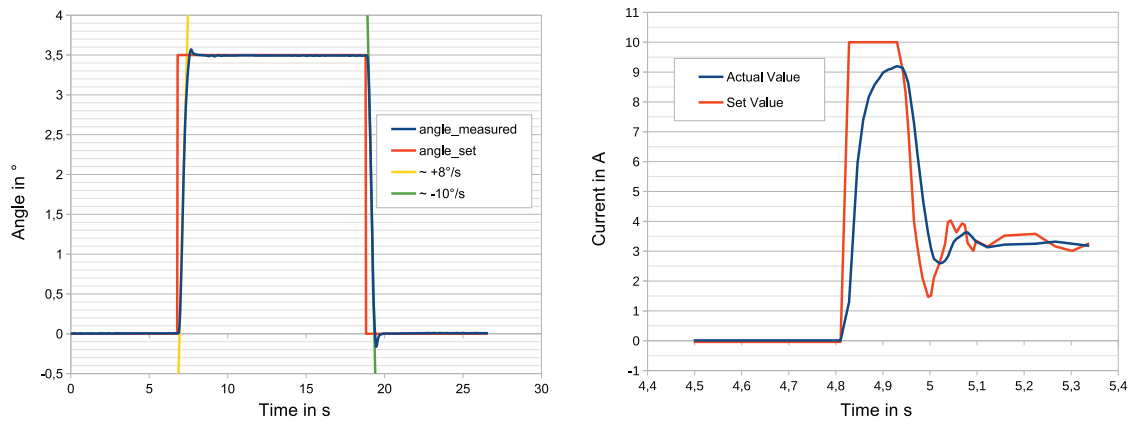


Figure 11: Left: Speed of displacement, Right: Current set value versus actual value

4 Conclusion

A 1 m spanwidth demonstrator is designed, manufactured and tested, including morphing hardware, sensors, redundant hydraulic actuation system and a control system.

The performed tests show the feasibility to use the FAMoUS principle to build a morphing winglet tab. The deflection size and control accuracy requirements are met and the design model is valid after the mentioned corrections. Regarding deflection rates the minimum requirements are met, while the higher deflection rates for load- and gust-alleviation can not be achieved with the current setup.

Summarizing the performed work, it can be stated that TRL 3 is reached, thus meeting the main objective of the experiments.

Furthermore future fields of research to achieve higher TRL are identified: A deeper understanding of dynamic behavior of the pressure cells has to be assessed, especially separating control-parameters and material properties as cause for lower dynamic performance of the system. The testing should address simulated aero-loads and a wider temperature range, as the current test are solely done at room temperature.

Regarding structural design and consequently the manufacturing process a reduction of manufacturing complexity as well as weight optimization should be investigated in more detail, especially addressing observed failure-modes (e.g. as occasional leakage) and aspects of repairability.

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