ACTIVE AERODYNAMIC COMPONENTS FOR AUTOMOTIVE APPLICATIONS – FRP SPOILER WITH INTEGRATED SMA ACTUATION

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ABSTRACT

This contribution focuses on the application potential of active fiber reinforced polymer (FRP) structures with integrated shape memory alloy (SMA) elements for new aerodynamic functions. The advantages of hybrid SMA FRP structures are highlighted and promising application concepts are discussed. Main focus is the development of an active aerodynamic profile representing e.g. rear spoiler. Beginning with the idea of an adaptive airfoil, able to bear an application relevant down force at a relatively high deflection, the design process starts with an evaluation of different airfoil actuation concepts. A SMA powered bending beam is a part of the airfoil itself. Applying the finite element method with a suitable model for the active hybrid material, an effective selection of material and design is possible. After manufacturing and assembling, the installation of an integrated hardware setup with power source, control and the active airfoil, demonstrating actuation on demand, verifies the potential of the new approach.

1 INTRODUCTION

In the field of solid-state actuators shape memory alloys (SMA) show an outstanding performance. They reach high actuation travel and stress levels at the same time. This leads to a high volumetric energy density of these actuator materials. In combination with comparable low specific weight SMAs are interesting candidates for lightweight products and especially applications where design space is premium. Major aspect limiting the application range is the available actuation frequency, however thinner SMA elements help to increase the actuation frequency and a wide range of actuation functions can be addressed. [1] Air flow deflectors driven by SMA elements like vortex generators [2, 3], turbine chevrons [4, 5], air inlet lips [6], and trailing edge flaps [7] have been investigated in the past. However, the actuating SMA elements are mainly connected in a discrete assembly to the structure resulting in a more or less complex mechanism.

To enable further improvements in terms of design-space requirements, light-weight potential and actuation possibilities, it is necessary to eliminate additional coupling elements and actuated assemblies, which add mass and bulk to the system. This can be realized by the direct integration of SMA elements in flat fiber reinforced polymer (FRP) components, turning these into active hybrid structures. These can be deflected by the SMA contraction in the bending beam layup of stacked FRP and SMA layers.

Composite materials such as FRP offer various possibilities to integrate SMA elements. But particular attention has to be paid to the load transfer between SMA actuator and the hosting structure, in order to avoid interface failure during activation. [8] The manifold design possibilities of FRPs contribute to the success of these materials. The material properties can be tailored by the selection of specific reinforcing material, its direction and volume content. [9] Especially in wire form high degree of adaptability of the active SMA elements can be achieved and the actuation can be designed individually for the specific application.

For an efficient design process reliable tools to enable a computer aided design by finite element method are required. A large number of material models for the SMA material itself is provided by literature [10], but the applicability of this models on the component level for FRP and SMA hybrid laminates is strongly limited. [11, 12] For laminar FRP components a blurred shell description is commonly used [13]. A suitable model, which meets the requirements of an efficient hybrid component design, is described in [14]. It is based on the characterization of the actuation behavior working against various spring stiffnesses.

With the load-conforming manufacturing approach and the suitable simulation model an important fundament is prepared for the transfer of active SMA FRP structures to new industrial applications.

2 AERODYNAMIC APPLICATION CONCEPTS

Active SMA FRP structures are of special interest for aerodynamic applications, as aerodynamics always deals with the interaction of an outer shape and airflow. The outer surface is usually built by several laminar components and for any situational adaption internal mechanics enable a moving of dedicated parts. Active SMA FRP technology enables the generation of complex curved shapes of laminar components on demand. Compared to common actuator solutions the direct and distributed actuation by SMA FRP structures shows several altered boundary conditions:

- No mechanics and couplings are required except an electrical connection
- The actuating force is distributed and not applied to two discrete points
- The number of parts is reduced
- The actuator can be individually tailored (material, active cross section, orientation)

This results in several advantages:

- Strongly reduced design space requirements, as only a slight increase of component thickness is necessary
- High lightweight potential, due to the high energy density of SMA and the absence of mechanical couplings
- Enhanced design variety due to a tailoring of surface bending/deflection
- Improved aerodynamical performance, due to continuous surface deflection without unwanted gaps or kinks
- Reduced complexity of assembly, achieved by reduction of part count

Usually SMA actuators are activated by joule heating via an electrical current. The above-mentioned advantages can lead to products with a better performance, enhanced functionality or even new functions can be addressed. The efficiency will be maximized if the actuation function is self-activated, e.g. by the use of waste heat. Especially actuation functions in connection with temperature control e.g. active air inlet vents benefit from self-actuation and/or self-control.

The reduced complexity of actuated elements and the reduced design-space and weight allow for new aerodynamic applications such as multi winglets or active trailing edge control (see Fig. 1). These new functions “on demand” can be linked to the current flight situation of an aircraft for example. A switch between multi winglet und single winglet would help to optimize the drag for both situations: cruise and take-off/landing [15, 16]. Trailing edge deflection can also have a high impact on the aerodynamic performance of aircrafts [7]. Vortex generators used on demand enable steeper and slower landing approaches without a drawback for the cruise efficiency [2, 3].

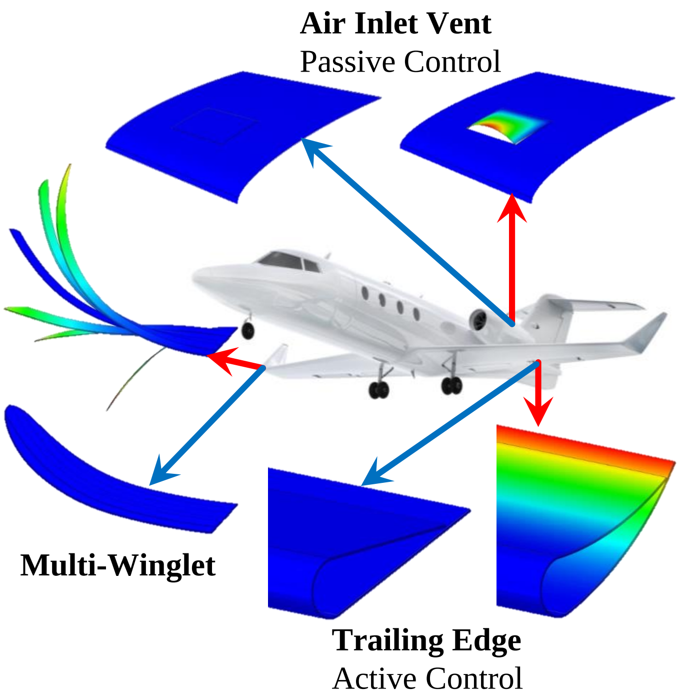

Fig. 1: Aerodynamic application concepts for active SMA FRP structures.

3 DESIGN AND MANUFACTURING OF THE ACTIVE AERODYNAMIC AIRFOIL

To highlight the potential of the active SMA FRP technology, a typical aerodynamic element in a car, i.e. an adjustable rear axle spoiler, typically used in modern sports cars, is chosen. In actuated state, the device should bear an aerodynamic pressure directed downwards of about 1 kPa at the trailing edge, resulting in approx. 10 kg at car with. Fig. 2 shows dimensions of the cross section and desired actuation range of the aerodynamic element. The outer shape of the airfoil is defined as simple as possible, to reduce tooling costs for the first prototype.

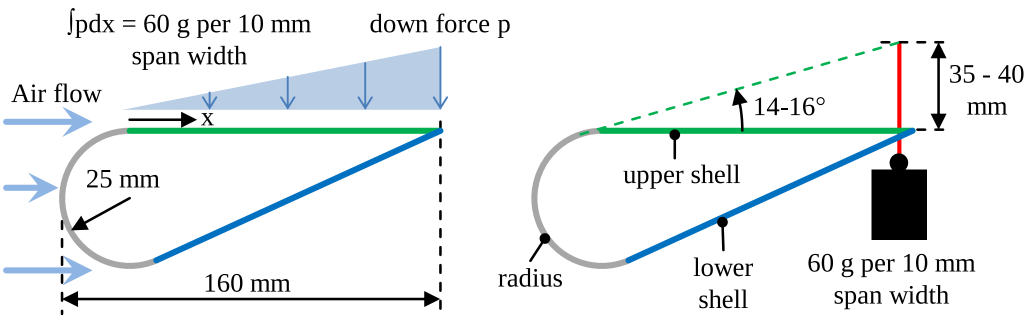

Fig. 2: Dimensions of airfoil and actuation target.

The simplification of the loading situation, by simulating the whole aerodynamic load via a simple weight at the very end of the structure over represents the real situation, as the aerodynamic loading would be distributed over the whole surface and only be 100% present at full deflection. This active aerodynamic airfoil can also be seen as the representation of the trailing edge of a wing or any other aerodynamic control surface of an aircraft as well. The working principle of a SMA actuated bending beam and five different concepts for an active airfoil are presented in Fig. 3. They differ in section types (closed (1,2) , filled (2) , open (3,4,5)) and in the positioning of the active SMA elements. Important aspects, which have to be considered for evaluation of the concept, are:

- Structural stiffness inhibiting edge deflection should be limited
- The outer surface should be flat and smooth

- Design complexity should be low with only a small number of relevant parameters

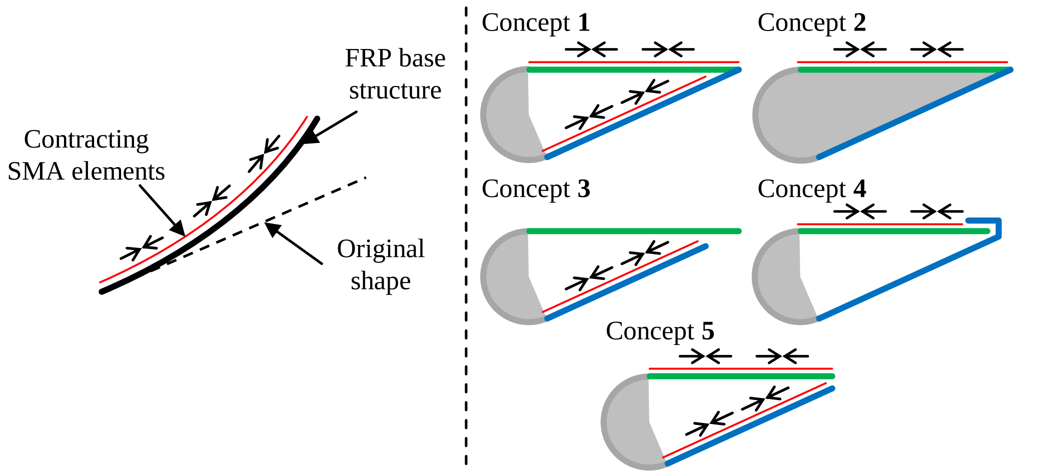

Fig. 3: Actuation concepts for an active airfoil by the use of SMA driven bending beams.

Concept 1 and 2 with closed or filled airfoil cross-sections will show relatively high mechanical resistance against an edge deflection, no matter where the active SMA element is located. Concept 3, 4 and 5 represent open profiles, which allow for a relative movement between the end of the upper and lower shell. The resistance against edge deflection therefore is mainly dependent on the stiffness of the shells, which can be tailored individually.

Concept 5 requires a coordinated actuation, which increases design complexity. Concept 3 and 4 are somehow similar, with variant 3 having 2 advantages: positioning the active SMA element at the inner surface of the shell avoids additional arrangements for having an aerodynamic smooth surface on top. Pushing upwards against the upper shell (concept 3) rather than pulling up the lower shell (concept 4) allows for a less complex interconnection between the two shells at the edge. Concept 3 is chosen as the most promising one.

A finite element method model for concept 3 is set up, as presented in Fig. 4a). The front radius is assumed to be rigid, thus the design space is limited to layup definition of the upper and lower shell. Furthermore the aerodynamic down force is modeled linear increasing towards the edge, representing altogether about 176 g for a width of 30 mm.

For easy manufacturing the active SMA layer is assumed to have one 0.5 mm thick SmartFlex® wire per 5 mm width. A comprehensive characterization of the actuation performance of the SMA elements led to material parameters (shown in Fig. 4b), which allow for a precise prediction of the deflection for distinct composite layups and actuation temperatures (presented for 100°C and 150°C).

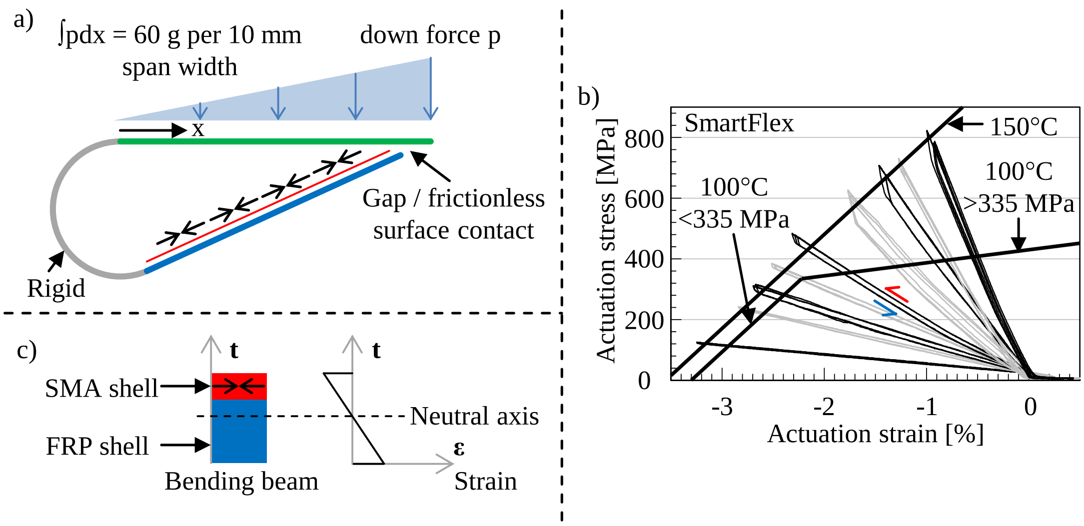

Fig. 4: a) Configuration for finite element model for design, b) Actuation characterization of SMA, c) Major influences on bending beam behavior.

Iterative simulations of the active lower shell are performed to select the optimal material combination. The loading situation is described by an external force and the elasticity of the upper shell interacting by a frictionless contact. The total deformation of our actuator is mainly influenced by the contraction of the active SMA material, its geometric position on the cross section of the bending beam and its resulting stiffness, as shown in Fig. 4c). The bending stiffness is mostly influenced by the material stiffness and the total thickness. Therefore four generalized situations can be considered:

1. Thin laminate with low stiffness
2. Thin laminate with high stiffness
3. Thick laminate with low stiffness
4. Thick laminate with high stiffness

The bending behavior of each situation can be described as follows:

1. High contraction of SMA combined with small distance to neutral fiber results in extremely high deflection.
2. Strongly reduced contraction of SMA combined with small distance to neutral fiber results in medium deflection.
3. Reduced contraction of SMA combined with high distance to neutral fiber results in medium deflection.
4. Extremely reduced contraction of SMA combined with high distance to neutral fiber results in minimal deflection.

Number 2 and 3 lead to usable deflection values while differing strongly in the stress levels generated by the SMA elements. Being placed near the neutral axis (2), the SMA elements will operate at a much higher stress level. This increases the risk for interface failure and hence reduces the number of possible SMA actuation repetitions. To realize desirable thick laminates with low stiffness (case 3), the use of high performance FRPs, such as polymers with continuous carbon fibers, is not beneficial. Fabrics with short fibers and/or reinforcing fibers with lower stiffness, such as glass fibers, are more promising. To minimize the influence of temperature on the mechanical properties, thermosets are recommended, as long as they exhibit a sufficiently high fracture strain.

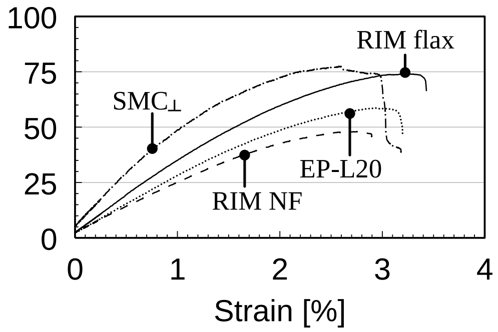

Fig. 5: Stress-Strain curves of different reinforced thermosets in 3-Point-Bending Tests.

The influence of various reinforcing fibers and resins on the stress strain behavior of FRP is illustrated in Fig. 5. Sheet molding compounds (SMC) in general have the lowest stiffness of thermoset GRFP, especially in cross direction with respect to the flow in the mold. The best suitable mechanical behavior, i.e. highest fracture strain and lowest modulus, is determined for a composite consisting of an epoxy based RIM resin and a flax mat. However, it has to be pointed out that - in addition to strength and strain requirements - numerous other constraints, e.g. media resistance, impact and damage tolerance behavior, wear, electrical properties, repair, recycling, manufacturing properties, availability and cost, have to be carefully considered for the final material selection of future commercial applications.

Besides the selection of most suitable materials a manufacturing concept for realization of the active airfoil is developed. The passive elements, radius and upper shell, are integrally manufactured;

the active lower shell is manufactured separately, as shown in Fig. 6. For the upper shell and radius a negative mold, representing the outer surface, is set up to ensure a high surface quality of the final part. For the active lower shell, the base laminate is manufactured as a flat sheet while the active SMA layer is applied in a second step on top. [8] The two parts are joined by laminating additional GFRP layers in the joining area. Finally, a painting with softening agent is applied to the outer surface.

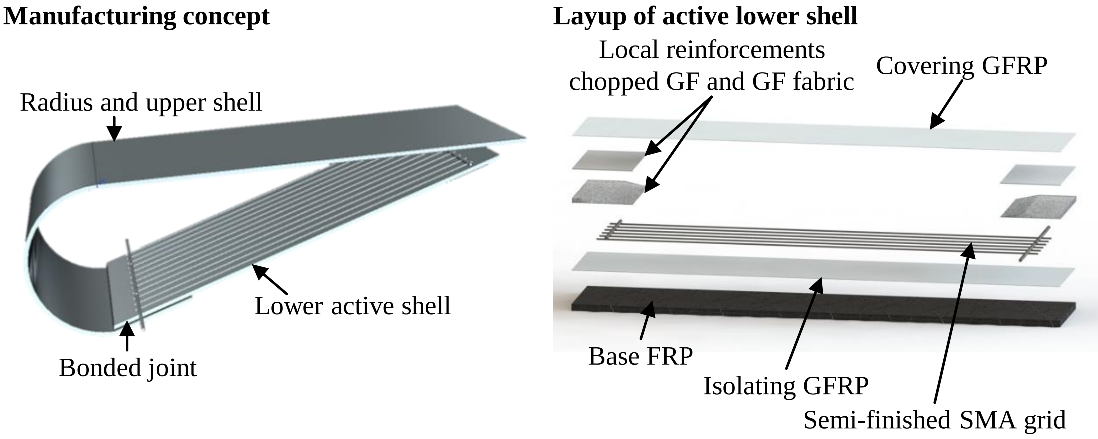

Fig. 6: Manufacturing concept of active airfoil. [8]

The simulated deflection for operation of the actuators at 100°C reaches 35 mm, meeting the target window. Taking into account the additional loading applied from the upper shell and the external load, the deflection will be reduced by approximately 15 %, while the stress in the SMA elements is increased by 7.7 %. These changes are rather small, due to the relatively soft upper shell and the high energy density of the SMA material, which makes it less sensitive to variations in loading. To further increase the deflection, also a heating of the SMA material above 100°C is possible. However, for the present design a further increase in contraction of the SMA elements (> 2,3 %) for temperatures above 100°C can bear the risk of permanent deflection of the FRP composite.

4 SYSTEM SETUP OF THE ACTIVE AERODYNAMIC AIRFOIL

To fulfill the original target, to demonstrate the major advantages of active SMA FRP structures for aerodynamic applications, a whole system is set up. The active aerodynamic airfoil is combined with a suitable power supply and a feedback control unit for operation of the airfoil. For quick joule heating the hardware setup uses a compact LiPo battery. The accumulator with 14 V and a capacity of 3800 mAh is sufficient for more than 150 actuation cycles, demonstrating the limited energy demand of the system. The feedback loop for on demand actuation at user input is realized with an ultrasonic distance sensor. Measuring the actual deflection, the current supply is switched off when a predefined deflection is reached. Secondly, the starting of a subsequent activation can be linked to a certain remaining deflection during the cooling cycle.

Fig. 7 shows the original and the deflected shape of the setup as well as the user interface (without the ultrasonic sensor).

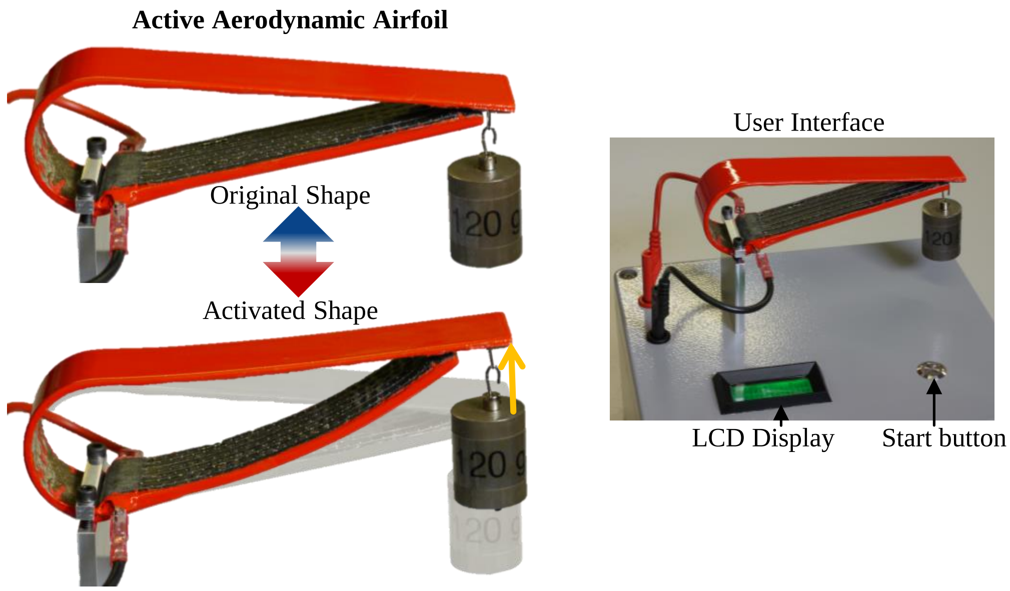

Fig. 7: Actuation behavior of completed active airfoil and the hardware setup.

5 CONCLUSION

The advantages of active SMA-FRP structures, particular for aerodynamic applications, are successfully demonstrated with an active aerodynamic airfoil, showing deformation of its cross section on demand. There are several advantages compared to conventionally actuated solutions, which are validated by the active airfoil:

- Strongly reduced space requirements
- High lightweight potential
- High design freedom of surface deflection
- Improved aerodynamic performance
- Reduced complexity of assembly

The required space and complexity of assembly is reduced by complete integration of the actuator in the lower shell of the airfoil. The lightweight potential is demonstrated by the ability of the airfoil, to lift a weight of 120 g over 10 mm up, which is 300 % of its own weight. Even for the present demonstrator configuration, which does not fully exploit the actuation potential, the aerodynamic pressure at the trailing edge can be assumed to 0.6 kPa. The curved shape on activation depicts the advantages for the aerodynamic performance and design freedom by the absence of gaps and kinks.

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