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NOVEL TAILORED SKIN SINGLE DUCT CONCEPT FOR HLFC FIN APPLICATION

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Abstract

State of the art HLFC suction panels are designed with an internal chambering to provide the cord-specific suction distribution on the outer skin. This leads to a number of constraints between aerodynamic, structural design and manufacturing. Also the manufacturing itself is highly complex due to a large number of internal chambers.
Current activities of the German Aerospace Center DLR have the goal to simplify this suction nose layout by omitting the internal chambers. For this reason the so called Tailored Skin Single Duct (TSSD) concept was developed. The TSSD is based on a multilayered tailored outer skin with an intrinsic pressure drop distribution. The outer surface is realized by a micro-perforated metallic foil to ensure a homogeneous control of the boundary layer. A specific laminate on the backside of the outer layer provides the necessary cord-wise suction distribution. By the use of this tailored outer skin, only one internal collector duct with a fixed plenum pressure is necessary.

1. Introduction

In order to reach the goals of Flightpath 2050, a significant decrease of fuel consumption of passenger aircrafts is mandatory. Today boundary layer laminarisation trough hybrid laminar flow control (HLFC) appears one of the most promising technologies to make the necessary step forward.
State of the art HLFC suction panels are designed with an internal chambering to provide the cord-specific suction distribution on the outer skin. This leads to a number of constraints between aerodynamic, structural design and manufacturing. Also the manufacturing itself is highly complex due to a large number of internal chambers.
Current activities of the German Aerospace Center DLR have the goal to simplify this suction nose layout by omitting the internal chambers. For this reason the so called Tailored Skin Single Duct (TSSD) concept was developed. The TSSD is based on a multilayered tailored outer skin with an intrinsic pressure loss distribution. The outer surface is realized by a micro-perforated metallic foil to ensure a homogeneous control of the boundary layer. A specific laminate on the backside of the outer layer provides the necessary cord-wise suction distribution. By the use of this tailored outer skin, only one internal collector duct with a fixed plenum pressure is necessary.
Due to this approach, the design of the HLFC leading edge could be optimised regarding structural requirements – like bird strike resistance and less weight penalty compared to non-HLFC leading edges. Also the manufacturing will be clearly simplified. Due to the absence of single chambers, another advantage is the possibility to create a full demountable leading edge design. This will enhance the possibilities of cleaning as well as the interchangeability or reparability.
The paper will give an overview of the aerodynamic layout of the tailored suction skin as well as the corresponding aerodynamic advantages of this design. Also the developed manufacturing process for the tailored outer skin concept will be presented. Furthermore a structural design concept of a leading edge for an HLFC fin application will be illustrated.

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2. Tailored Skin Single Duct concept description

The Tailored Skin Single Duct (TSSD) concept is based on a multi-layer outer skin, which provides an intrinsic pressure drop. This property of the outer skin leads to two major advantages:

1) The aerodynamic design and the structural design are completely independent and can be optimised separately. An internal chambering with a number of tight chambers is not necessary. Furthermore the aerodynamic driven suction velocity on the outer skin (and therefore the pressure drop distribution) can be chosen arbitrarily along the spanwise and/or chordwise direction.
2) The manufacturing and the maintainability increases dramatically. With the absence of tight chambers it is also possible to realize the complete leading edge in a demountable manner. With this feature the leading edge (and especially the outer skin) could be cleaned, if necessary. Individual parts are exchangeable and can be replaced, after local damages occur by hail strike or small bird strike impacts.

Figure 1 shows the basic layup of the TSSD outer skin. The first layer is a thin micro perforated foil. The foil is perforated with 50 µm holes by fine etching. The ultra-high quality and reproducibility of the perforation technology leads to a homogeneous suction of the boundary layer. Since the selected process is well established and industrialized a high production rate is feasible. The second layer is responsible for the pressure loss distribution of the TSSD outer skin. It is a metallic mesh with a tailored number of wire threads in warp direction. By varying the number of wires the pressure loss of the mesh is adjustable. The use of very small wires gives the possibility for a fine adjustment of the pressure loss. The third and fourth layer of the outer skin gives mechanical strength and stiffness to the laminate. It is a metallic fabric with thicker wires than the second layer. Finally all single layers are joined with a diffusion welding process. With this process the single layers are joined extensive on the one hand and create a permeable laminate in the other hand.

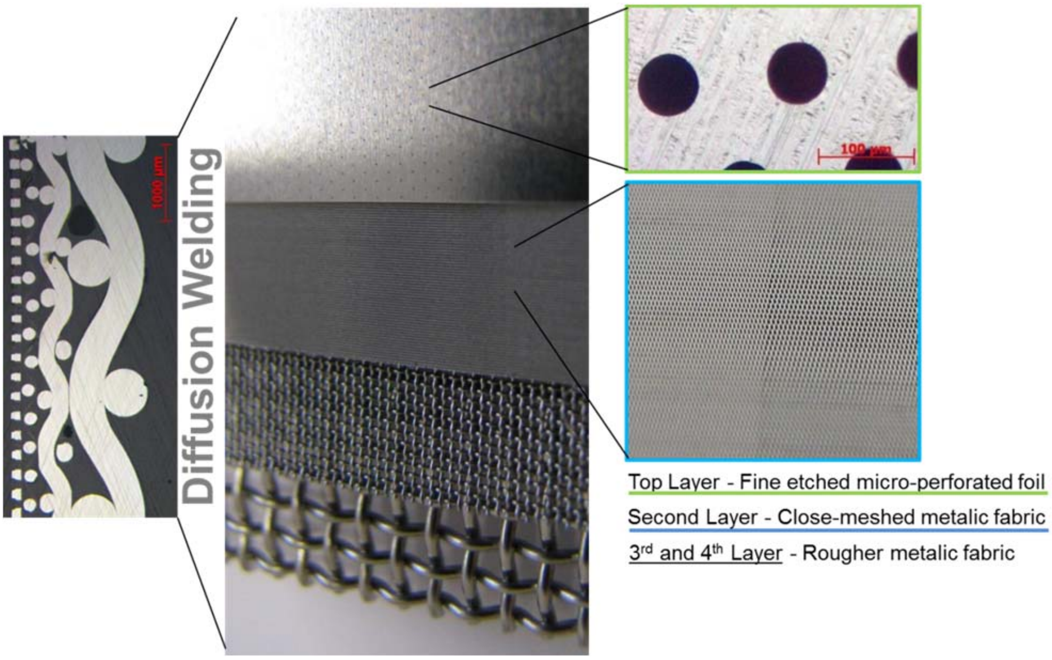

Figure 1: TSSD outer skin lay-up

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3. Aerodynamic design/layout

Specific design tools are necessary for the layout of boundary layer suction systems following the TSSD concept. Here, one has to distinguish between the outer flow about the surface of the aircraft component to be laminarized (aerodynamics) and the internal flow, i.e. sucking the air through the porous skin into the collector duct (flow technology). The present study deals with the latter problem while it is considered that the outer flow is well known from a detailed aerodynamic design or analysis of the complex aircraft configuration. This includes also the prescription of a suction mass flow rate in chordwise direction (or suction velocity distribution, respectively) that is optimised for a maximum of laminar boundary layer flow on the aircraft component under consideration. Here, the TSSD concept was developed for the fin of a short and medium range transport aircraft of the A320 type as a first target application but other components like tails or wings can be treated in exactly the same manner.

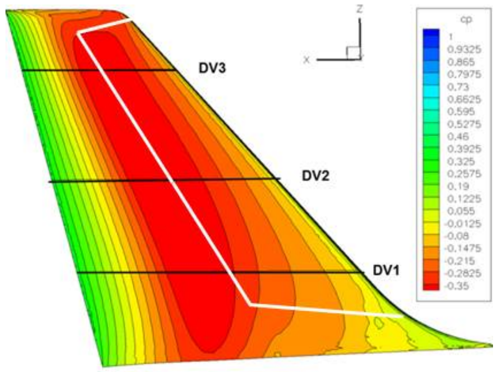

Figure 2: Surface pressure distribution in terms of pressure coefficient c_P on laminar fin design from [1]; white line marks transition from laminar to turbulent flow

Starting point of any suction skin design is the surface pressure distribution, here shown in Fig. 2 for the fin in terms of the pressure coefficient cP. It was calculated with the DLR flow solver Tau for a complete aircraft configuration at its design point, so the interference effects are resolved properly. All further steps of the skin layout will exemplarily be shown for the streamwise cut DV2, see the cross section and the extracted pressure distribution in Fig. 3. Additionally, the aerodynamic design delivers a suction velocity distribution (Fig. 4, red line) that is capable of delaying laminar to turbulent transition in cut DV2 down to a chordwise position of x/c = 0.493. It can be seen that suction is applied only on the first 18% of the chord, i.e. on the nose box of the fin.

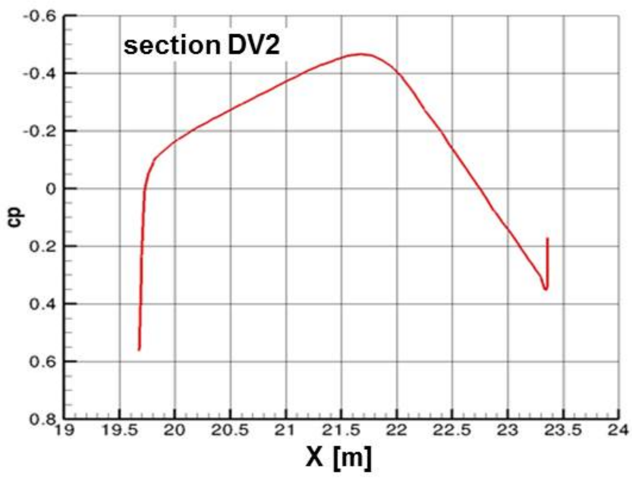

Figure 3: Extracted surface pressure distribution in cross section DV2 of laminar fin

Of course, sucking air into the fin’s nose needs a pressure difference Δp between the outer surface and the interior, with the low pressure in the box. The outside static pressure along the surface changes with arc length in chord

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direction while the internal plenum pressure (provided e.g. by a compressor or pump, respectively) is constant, see also Fig. 4.

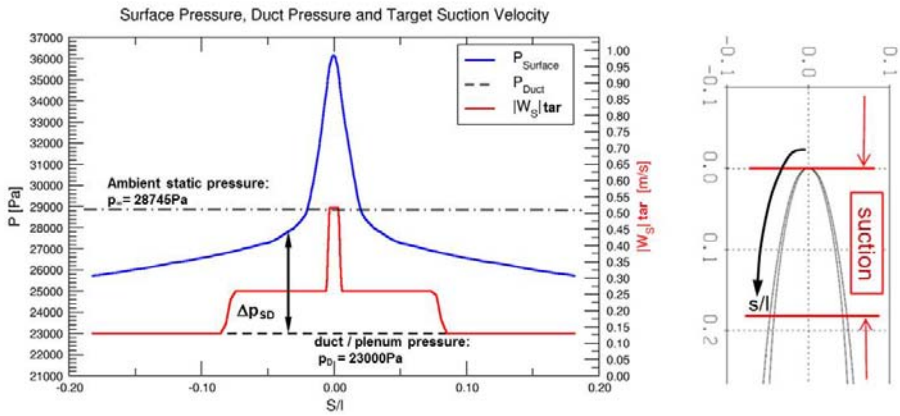


Figure 4: Surface pressure, duct pressure and target suction velocity vs. arc length along contour of cross section DV2

The objective of the skin layout then is to find a porous surface that, with a given Δp at a certain position s/l, has a flow resistance which delivers the suction velocity wS prescribed in the aero design. As was described in the previous chapter, the flow resistance (or pressure loss characteristics, respectively) of the TSSD concept can be tailored by varying the density of the filling threads in the second layer of the multi-layered skin build-up. By pressure loss characteristic of a suction surface we understand the dependency of the pressure loss Δp as a function of the mean suction velocity wS through a (homogeneously) porous surface. By numerous measurements of test samples with the DLR Large Flow Meter (LFM, see Fig. 5 and Fig. 6 as an example) it was found that the pressure loss characteristics of hybrid suction skins can be expressed by a simple quadratic function, i.e.

$$\Delta p = A \frac{\mu_s}{\mu_0} w_s + B \frac{\rho_s}{\rho_0} w_s^2$$

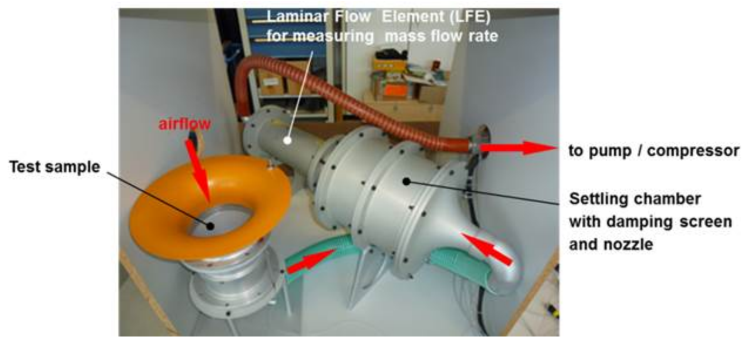
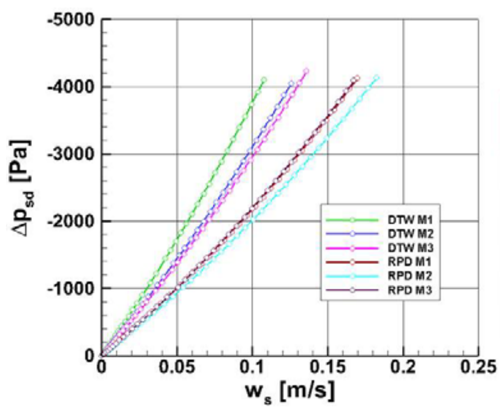


Figure 5: DLR Large Flow Meter (LFM) for measuring pressure loss characteristics of suction skins



Sample	A [Pa s/m]	B [Pa s²/m²]
DTW-M1	-31446.44	-61330.57
DTW-M2	-26619.43	-43726.50
DTW-M3	-25256.73	-42670.90
RPD-M1	-18173.74	-35870.69
RPD-M2	-17066.83	-30474.64
RPD-M3	-18363.73	-35981.51

Figure 6: Pressure loss characteristics of six test samples with varying buildup of hybrid layers

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Here, constants A and B are specific for a certain hybrid buildup and are determined from the measurements in the lab at ambient conditions corresponding with standard atmosphere at sea level, while viscosity ($\mu/\mu 0$) and density ($\rho/\rho 0$) ratios are corrections needed to adapt the characteristics for conditions at flight altitude. The goal then is to find a chordwise distribution of hybrid materials with varying A and B that matches the target suction velocity distribution as good as possible. This is shown in Fig. 7, where we can see the target suction velocity distribution (black line) in comparison with the suction velocity that can be realized using hybrid materials with varying pressure loss characteristics (colored lines). As a final step of the design it is checked, whether the realized suction velocity distribution leads to a delay of the laminar turbulent transition as it was projected in the aero design. For DV2 the transition prediction code delivered the onset of turbulent flow at a chord position of x/c = 0.486. The deviation from the target is very small and lies within the uncertainty of the transition prediction methodology. It should be noted that in the present case no change of the hybrid layout in spanwise direction was necessary. However, with the TSSD concept this is also possible which might become an important additional option in the design of chamberless suction systems of wings.

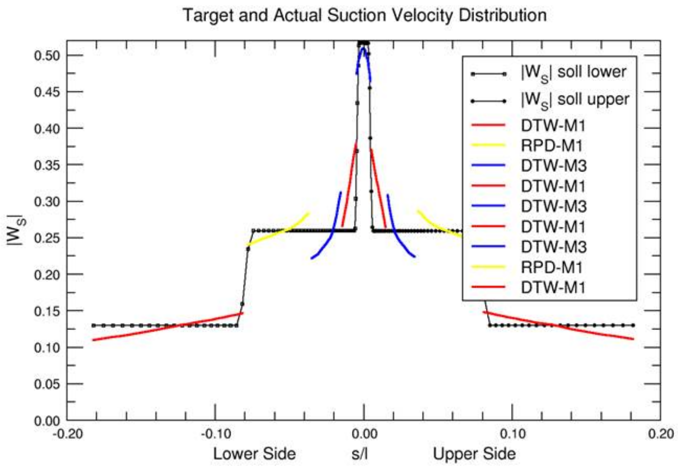

Figure 7: Target and actual suction velocity vs. arc length along contour of cross section DV2

4. Structural design

4.1 Structural design concept

Beside aerodynamic requirements the leading edge of tails and wings has to fulfil structural aspects. One of the most challenging design criteria is the high velocity impact due to bird strike. In this case the leading edge has the function to absorb or deflect the impact energy in order to protect the load carrying structure in behind the leading edge. The deflection of the impact energy has the advantage that not the complete energy has to be absorbed by the leading edge and primary structure (e.g. the box of the tail or wing).
Current HLFC suction systems adjust the pressure distribution by individual pressure chambers located under the surface, each working at a specified suction velocity. Since the pressure chambers have to be sealed among each other, these systems go along with great structural restrictions. The structure under the outer skin has to follow the shape of the chamber arrangement. With the novel TSSD concept it is possible to vary the suction velocity through the outer skin directly within the surface.

From structural side of view the TSSD fin application consists of three different modules as shown in Figure 8: the outer skin, the splitter and the ribs. While the contour of the outer skin is given by the profile design the underlying structure is almost constraint free. In case of a bird strike a crash-element – a so called splitter or deflector - was designed, located under the surface. It has the function to deflect the bird so that less energy gets absorbed by the aircraft structure [2]. This component is already designed to deal with this dynamical load condition and won't be change in the current process.

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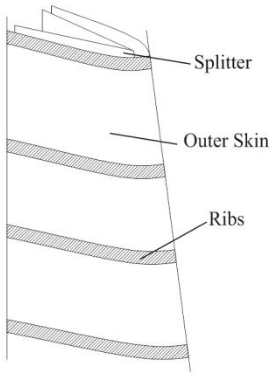

Figure 8: Modules of the novel leading edge design

4.2 Structural optimisation

Hence the design below the fin's surface is no longer constrained by the pressure distribution, new arrangements of the supporting elements are feasible. In order to find the best design for the HLFC fin application a structural optimisation tool is developed and the current state is applied to the present problem.
The optimisation tool consists of two major sub-processes. At first all the important boundary conditions have to be gathered while given constrains should be considered and implemented into the process. The parameter/parameters to be optimised have to be specified along with a reasonable range of values. All these information are transformed by individual tools to create input files for further processing. These subroutines were created using python. The second part is the optimisation loop itself. In an iterative process the design variables are varied in between their boundaries and the solution is analysed and compared to the problem's target. The calculations are carried out in ANSYS, the analysing and adjustment of the variables is done with routines created with the python framework.
For the presented case one important design point is the waviness of the surface during cruise condition while the HLFC system is active. Since a specific HLFC criteria for waviness is not elaborated so far, the well-known waviness criteria for natural laminar flow profiles is used [3]. Here a maximal amplitude of 2mm and maximal gradient of 0.005 are critical values and should not be exceeded. Limitations to that formulation are known [4] and more accurate requirements are researched at the DLR.

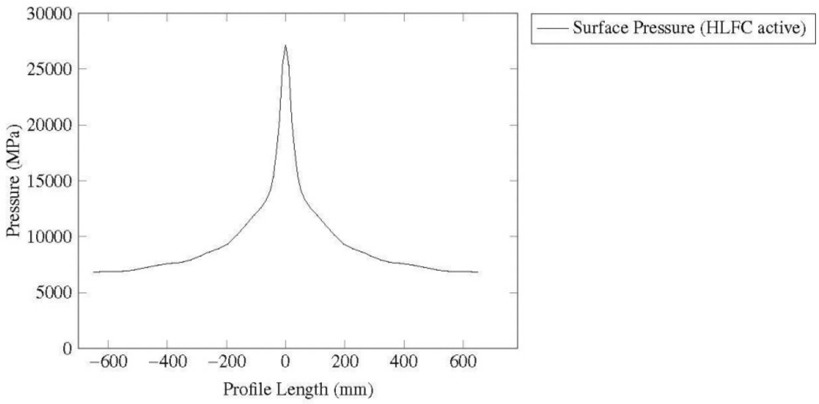

Figure 9: Pressure distribution for cruise condition and an active HLFC-System

Applying the optimisation tool to the present problem one important boundary condition is the pressure profile that is shown in Figure 9. It shows the calculated pressure for cruise condition and an active HLFC-System. Since the splitter is designed for a dynamic load, its geometry is kept constant in this static optimisation process. That leaves the arrangement of the ribs is to be examined and adjusted. To reduce factors of influence only the number of the supporting elements and their angle are reviewed. The number of ribs was set to vary from 4 to 10 while the range of their angle was defined between 0° and 50°. The starting value (0°) represents an alignment in streamwise direction. Figure 10 shows an extract of different geometry variations.

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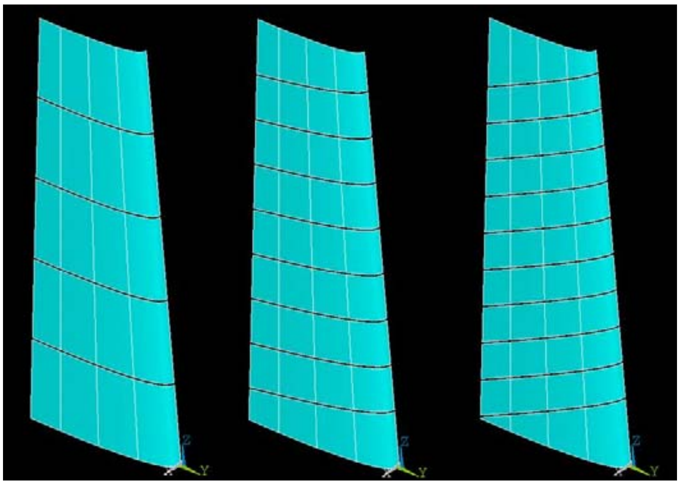

Figure 10: Example of various designs

The displacement of the outer skin is shown in Figure 11. When the iterative loops start the highest deformation is present in the lower section. With an increasing angle the maximum value is moving to higher location due to the area reduction of the lower section.

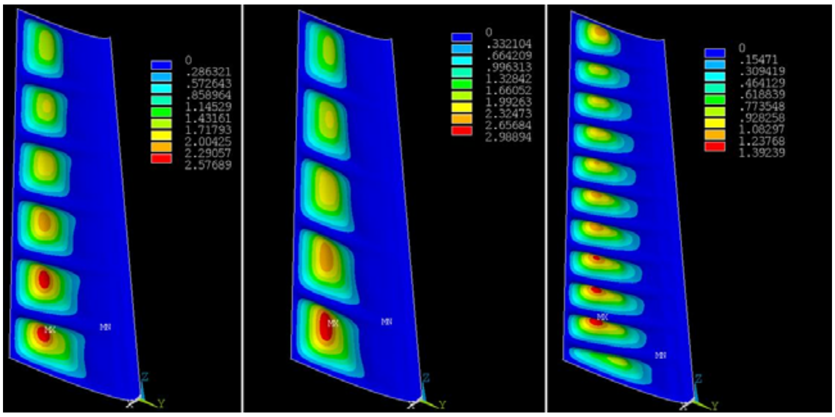

Figure 11: Maximum deflections for the configuration of 4, 5 and 10 ribs (left to right) at different angles

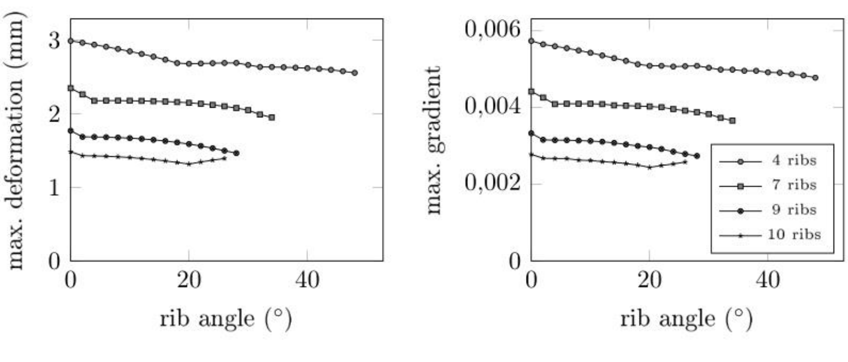

Figure 12: Maximum deformation and maximum angle for different rib configurations over the adjusted angle

Increasing the angle of the ribs leads to a decrease in the deformation that goes along with a reduction in the gradient as presented in Figure 1.For the case of 10 ribs an augmentation for both values is present at an angle of 20°. That is caused by the fact that the distance between the ribs is kept constant and the area of the upper section increases as the

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lower one declines. Figure 13 shows the maximal deformation for each rib number case together with the maximal deformation given by the waviness criteria. All values are taken by the best angle setting. The maximal gradient of 0.005 is underrun at a higher level and therefore not necessary for the presented case. For the present problem a design of 7 rips at an angle of 34° is favourable.

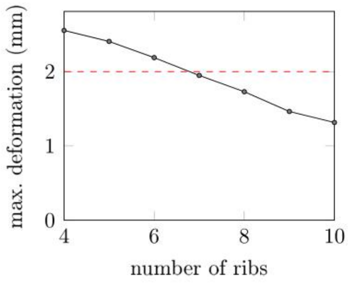

Figure 13: Maximum deformation over the number of ribs

Further expansions will be implemented in a future version with the aim to optimise the structure for example by reaching the same deformation in each segment. One important constraint for the design of aircraft structures it the weight of the final assembly. Therefore another tool is built to extract the weight out of the FEA model while an empirical model determines the increase due to joining elements

4.3 Demountable leading edge concept

Beside aerodynamic and manufacturing challenges, also maintenance and repair issues arise with the application of HLFC technology. Contamination of the micro perforated outer skin caused by dust and insects may lead to a reduced function of the HLFC system like small damages as a result of hail strike. Conventional non-HLFC leading edges are designed to resist these environmental influences or can be cleaned easily. State of the art HLFC solutions are designed as a closed construction with internal chambers and non-detachable joints. The cleaning of the leading edge or the exchange of single components is not feasible.
The TSSD concept offers the possibility to realise a demountable leading edge design. Because of the absence of internal chambers there is no need for an internal sealing. Thus the application of detachable joining methods is possible. The basic assembly process of such a demountable HLFC leading edge could be seen in Figure 14 and is divided into the following steps:

1) Laser welding of screws on the backside of the TSSD outer skin
2) Forming the outer skin into the aero shape
3) Positioning the formed outer skin in a female tooling
4) Assemble the inner structure, e.g. stiffener rib (join with the outer skin - screwing)
5) Assemble the splitter (join with inner structure and outer skin - screwing)
6) System installation
7) Mounting the leading edge on the tail plane

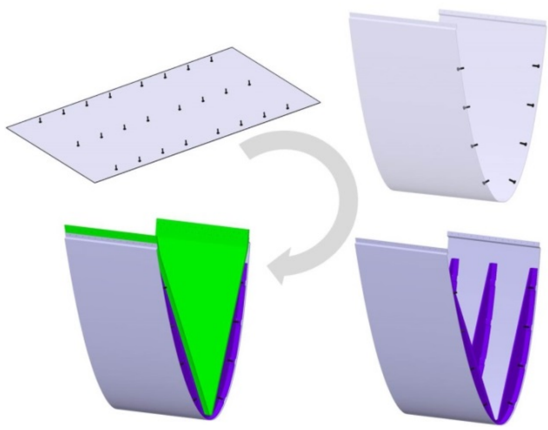

Figure 14: Manufacturing and assembly concept

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One of the most important detail for the demountable concept is the joining of the outer skin with the structure in behind. Like mentioned before, for the TSSD concept a screwable joining element was chosen. With a laser welding process the joining element can be welded on the backside of the outer skin, which can be seen in Figure 15. The advantage of this method is the good mechanical link in one hand, but a still permeable outer skin in the other hand. Figure 16 shows the cross section of the joining method.

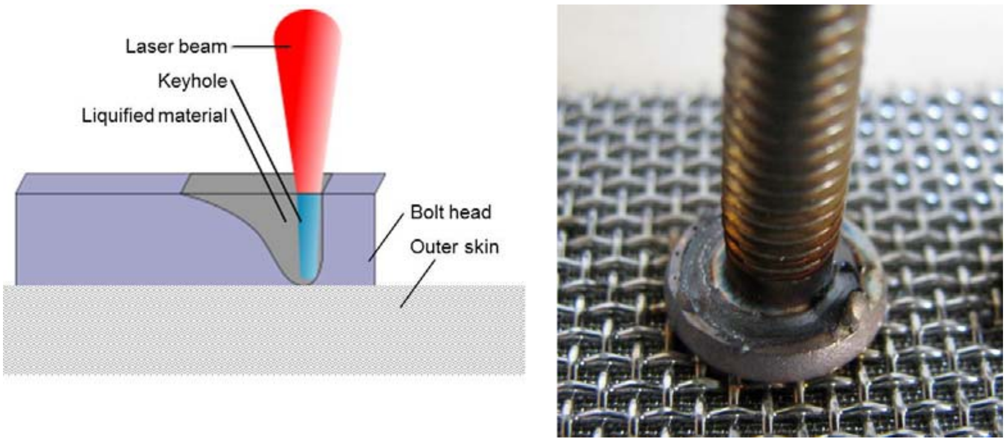

Figure 15: Joining process for outer skin

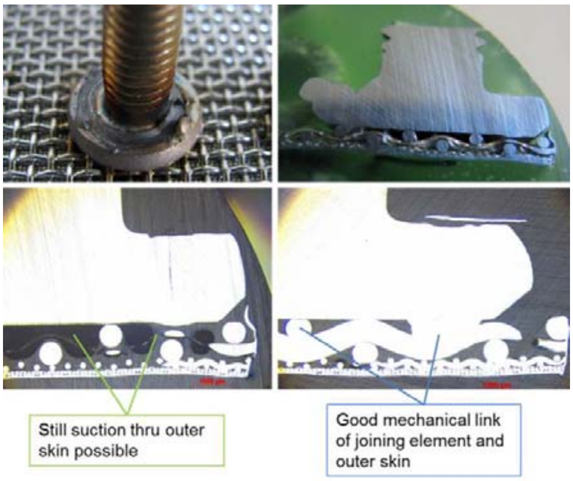

Figure 16: Laser joint cross section

With the described welding process it is possible to mount the outer skin with the inner structure, in this case with a stiffener rib like mentioned in chapter 4.3. Figure 17 shows a possible detachable joint of the outer skin and the rib.

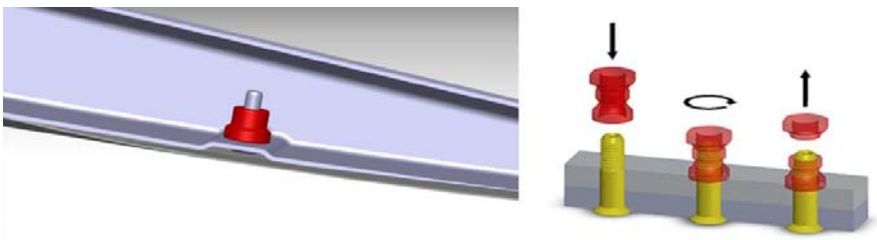

Figure 17: Demountable joining of outer skin with inner structure [5]

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5. Conclusion and Outlook

The TSSD concept offers a number of advantages compared to state of the art HLFC designs. First trials show the feasibility of the manufacturing process for the multi-layered outer skin, consisting of different metallic meshes and a micro perforated cover foil. The pressure drop is realizes within the outer skin segment that was examined and validated by an demonstrating structure. Flow tests show the outer skin matches the aerodynamic requirements regarding pressure drop.
The aerodynamic design process for HLFC leading edges was adapted to the TSSD concept. With the developed tools an aerodynamic concept for the fin application was designed, considering the measured flow characteristic of the outer skin material.
To make use of the minor design restriction a structural optimisation tool for HLFC leading edges was developed. With this tool an optimized design proposal for the inner structure was done.
Next steps will be the manufacturing demonstration of a complete leading edge segment. Also physical tests regarding high velocity impact are scheduled. The up-scaling of the manufacturing of the outer skin will also be a challenge. The overarching goal is the validation of a real scale leading edge in a wind tunnel experiment.

6. Acknowledgement

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