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# Cost-effective HLFC design concept for transport aircraft

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## Abstract

Resource-efficient flying is a central goal of current and future developments in aviation. Laminar technology is one of the most promising ways to contribute for the achievements to reach the goals of Flightpath 2050. The hybrid laminar flow control (HLFC), based on the combination of active flow control by boundary layer suction and natural laminar flow downstream, is a favourable way to laminarize leading edges with large sweep angle.
While the resistance-reducing effective of HLFC technology has already been proven with wind tunnel and flight tests, solutions for the cost-effective production are still subject of current developments. The particular difficulty lies in the combination of industrially producible designs while maintaining the aerodynamic performance.
For this purpose, DLR is developing a leading-edge design, based on a cost-effective, micro-perforated outer skin with intrinsic pressure drop distribution. Furthermore the leading edge will be fully demountable for maintenance and cleaning reasons. The resulting combination of low manufacturing and operational costs should leverage the breakthrough of HLFC technology for industrial application.

In the following paper the aerodynamic and structural design of the leading edge as well as the manufacturing technology of the outer skin are described. In addition the structural concept for fin application is presented.

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## Keywords

Hybrid laminar flow control, boundary layer suction, leading edge, design concept, chamberless

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## 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.

## 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 (green framed) 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 (blue framed) 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.

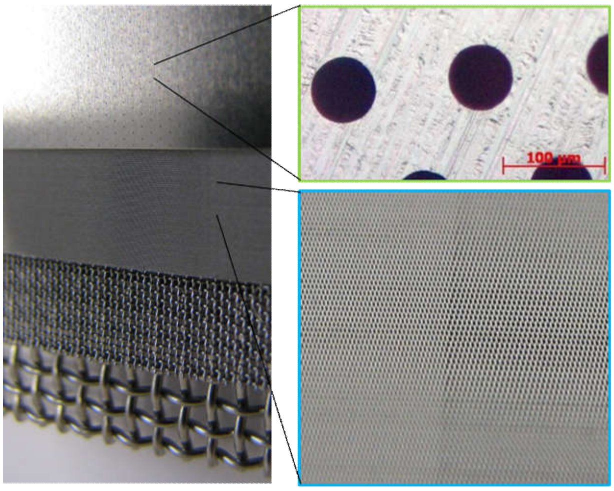


**Figure 1: TSSD-outer skin lay-up**

## 3. AERODYNAMIC DESIGN AND 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.

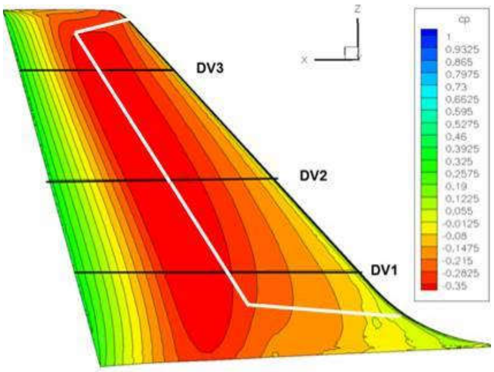


**Figure 2: Surface pressure distribution in terms of pressure coefficient cP on laminar fin design from [1]; white line marks transition from laminar to turbulent flow**

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.

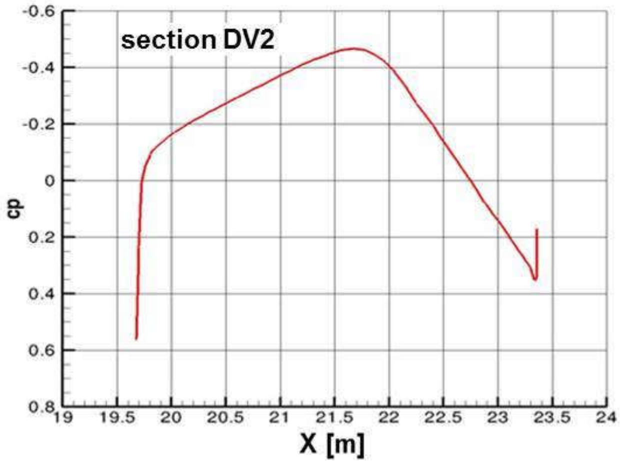


**Figure 3: Extracted surface pressure distribution in cross section DV2 of laminar fin**

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

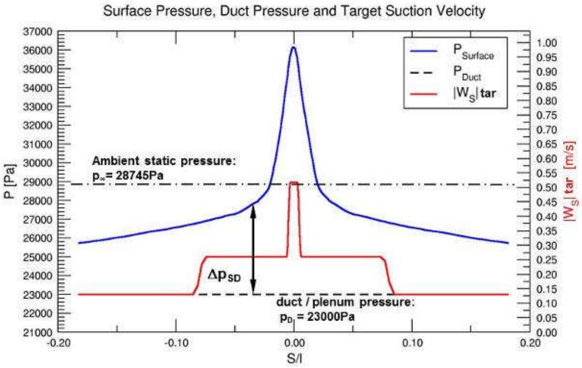


**Figure 4: Surface pressure, duct pressure and target suction velocity vs. arc length along contour of cross section DV2**

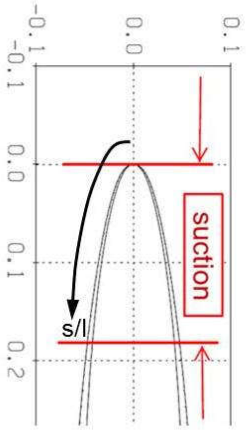


**Figure 5: Suction area on leading edge**

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. 6 and Fig. 7 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.

$$\Delta p = A \, \frac{\mu_s}{\mu_0} \, w_s \; + \; B \, \frac{\rho_s}{\rho_0} \, w_s^2 \qquad (1)$$

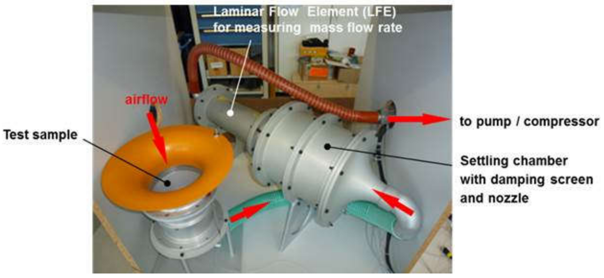
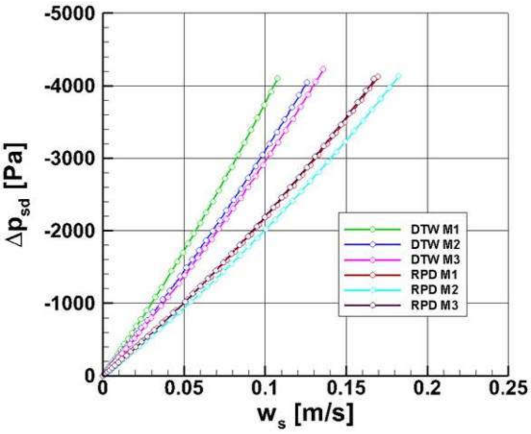
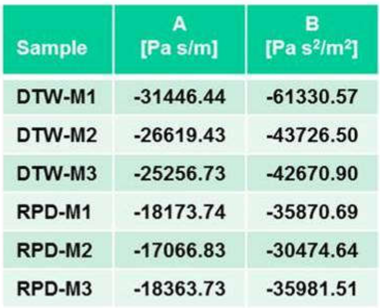


Figure 6: DLR Large Flow Meter (LFM) for measuring pressure loss characteristics of suction skins





| 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 7: Pressure loss characteristics of six test samples with varying buildup of hybrid layers

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 (μ/μ0) and density (ρ/ρ0) 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. 8, 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.

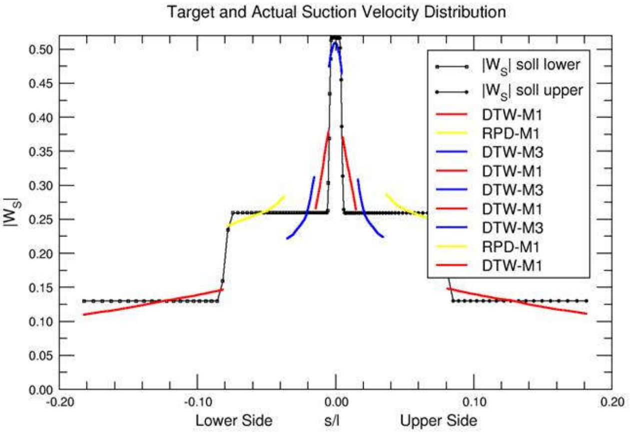


Figure 8: Target and actual suction velocity vs. arc length along contour of cross section DV2

## 4. STRUCTURAL DESIGN CONCEPT

### 4.1 DYNAMIC LEADING EDGE DESIGN

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 9: 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].

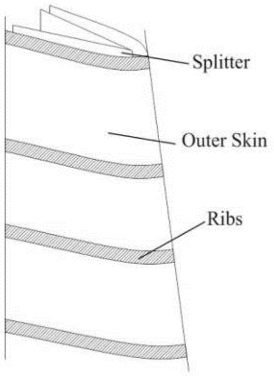


**Figure 9: Modules of TSSD leading edge design**

To take advantage of the specific possibilities, opened up by the chamberless HLFC design, a structural optimization of the leading edge was done [3].

### 4.2 DESIGN OPTIMIZATION

With the aim to find the best design for the HLFC leading skin - considering the weight and the aerodynamic constrains - a multidisciplinary optimization was set up. Since the rib layout was already found to be favourable for the considered LE, the individual parameters of this build-up were taken as design variables for the optimization problem. Two boundary conditions were analysed: The static strength and the transition point describing the laminar flow region.

After the geometry was generated the pressure load was applied to the LE outer skin and the deformations as well as the stresses/strains were calculated using FE-analysis. The stresses were used to evaluate the strength of the part while the deformations are imported into the aerodynamic tool in order to get the length of the laminar flow region.
The new deformed shape of the outer skin was used to create a new pressure distribution on the surface.
Then the crossflow and Tollmien-Schlichting instabilities are calculated to find the point of transition.
After the results were generated the design variables are changed and a new geometry is generated for the next optimization loop.

### 4.3 DEMOUNTABLE DESIGN

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 Fig. 10 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

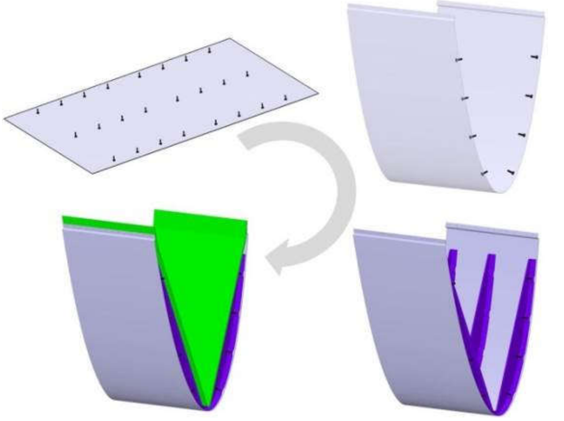


**Figure 10: Manufacturing and assembly concept**

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 Fig 11. The advantage of this method is the good mechanical link in one hand, but a still permeable outer skin in the other hand. Fig. 12 shows the cross section of the joining method.

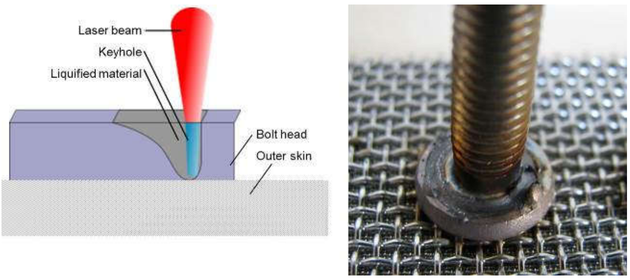


**Figure 11: Joining process for outer skin**

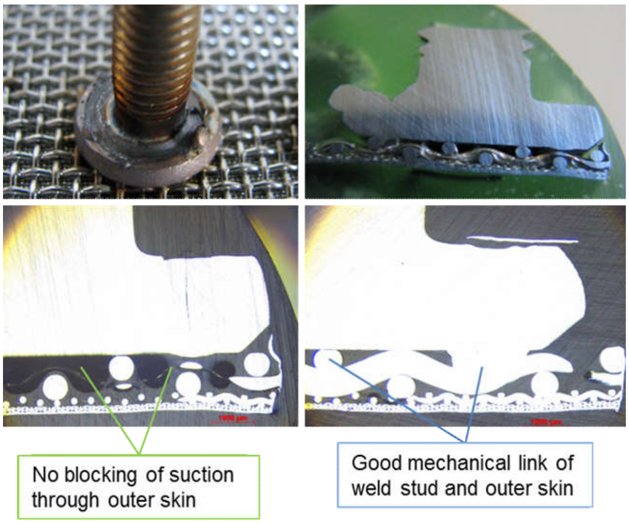


**Figure 12: Cross section of the laser joint**

With the described welding process it is possible to mount the outer skin with the inner structure, for example with a stiffener rib. Fig. 13 shows a possible detachable joint of the outer skin and the rib.

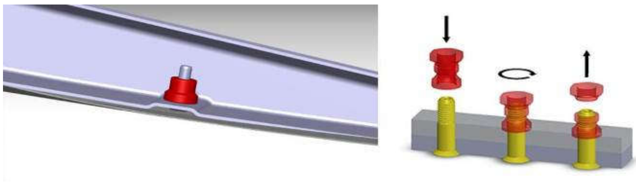


**Figure 13: Demountable joining of outer skin with inner structure [6]**

To demonstrate the TSSD concept for the fin application, the manufacturing of a real scale demonstrator was started. Fig. 14 shows the TSSD concept, formed in the shape of a typical vertical tail plane leading edge. Also the laser welded joining elements can be seen. Furthermore the assembled stiffener elements are shown. The ribs consisting of carbon fibre reinforced thermoplastic (CF-PEEK) were formed in a press process.

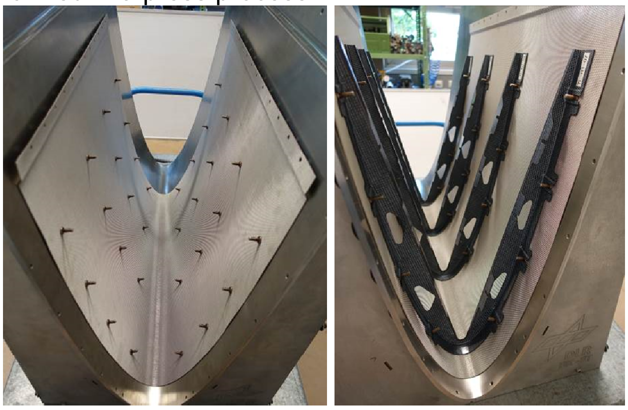


**Figure 14: Formed outer skin with welded screws (left), stiffener ribs in formed outer skin (right)**

## 5. CONCLUSION AND OUTLOOK

The TSSD concept offers a number of advantages compared to state of the art HLFC designs. Manufacturing trials show the feasibility of the production process for the multi-layered outer skin, consisting of different metallic meshes and a micro perforated cover foil. 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 an optimized design proposal for the inner structure was done.

Current work is focused on the manufacturing of a demonstrator of a TSSD leading edge segment. The up-scaling of the manufacturing process of the outer skin will be a further challenge.

The overarching goal is the validation of a real scale leading edge in a wind tunnel experiment.

## 6. ACKNOWLEDGEMENT

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