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STRUCTURAL DESIGN AND TESTING OF A TAILORED SKIN SINGLE DUCT (TSSD) FIN APPLICATION

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Abstract

In order to increase the efficiency of air travel and to reach the goals of the European Strategy Flightpath 2050, the fuel consumption of modern airplanes has to decrease significantly. One approach towards a more ecological aircraft design is the boundary layer laminarization trough Hybrid Laminar Flow Control (HLFC) technology that reduces the aerodynamic resistance by enlarging the laminar flow region. A promising way to integrate the HLFC method into an aircraft structure is the chamberless so called Tailored Skin Single Duct (TSSD) concept developed at the German Aerospace Center (DLR).

In the following text the makeup of the system is outlined and the applied boundary conditions are presented. The aerodynamic concept is discussed and the undertaken experiments to characterize and configure the outer skin are explained. Due to the porous outer skin a sealing strategy is required and experiments were carried out to find passable material properties. That is also driven by the idea to make the system detachable for service and maintaining duties. Since the new design comes with fewer restrictions to the underlying structure compared to the state of the art chamber-setup, an optimization tool was developed and used to find an efficient makeup.

1 Introduction

One way to increase the efficiency of modern airplanes is to reduce the aerodynamic resistance by enlarging the laminar flow region. For example 8% of fuel could be saved by expanding the laminar region up to 20% [1]. The HLFC technology manipulates the boundary layer using two effects: In the front part instabilities on the leading edge are prevented by suction through the outer skin, while the flow maintains its laminar state afterwards by a favorable profile geometry. State of the art suction panels realize a beneficial pressure distribution at the surface by internal chambers each providing a cord-specific suction distribution on the outer skin. The latter configuration was already tested in a flight experiment two decades ago on an A320 fin [2] and later on a Do228 [3] where the feasibility was demonstrated. Further investigations to improve the chamber-design were carried out and tested in a wind tunnel experiment with promising results [4].

However the chamber design leads to a multitude of additional constraints that have to be considered during the design and manufacturing process. With the aim to simplify the HLFC-design the Institute of Structures and Design and the Institute of Aerodynamics and Flow Technology at the German Aerospace Center (DLR) developed the so called Tailored Skin Single Duct (TSSD) concept [5]. The main component of this building technique is a multilayer tailored outer skin with an adaptable intrinsic suction velocity to adjust the pressure distribution on the surface. For the TSSD design no chambers are required and just one sealed plenum at a constant pressure has to be present. Due to a loss of constraints the underlying structure is simplified and new design options are feasible.

In the present work, the design process is shown regarding the requirements for the HLFC system focusing on dynamic and static loads while active suction is used in the front part up to $\frac{s}{l} = 0.2$ of the profile depth. The structure underneath the outer skin was designed using different optimization methods that will be illustrated. Statistical Methods were used to automate the process and to accelerate the search for an appropriate geometry. A basic requirement in aircraft certification is the bird-strike capability. Forward facing structures like the leading edges of the empennage have to withstand a bird-strike. During the assembly of the demonstrating structure, the manufacturing process was reviewed and analyzed. It is planned to integrate the HLFC technique on a leading edge of a fin with the dimensions of a short- or midrange aircraft like the A320.

2 Tailored Skin Single Duct Concept

The Tailored Skin Single Duct (TSSD) concept is based on a multi-layer outer skin that is able to provide an intrinsic pressure drop, while only one constant plenum pressure is applied.

This leads to the advantage that the underlying structure is independent of the intended pressure profile on the surface and can be arranged in a free manor. No individual chambers or bounds to influence the suction velocity are present, since the pressure distribution can be adjusted by a modification of the tailored outer skin.

Figure 1 shows the layup of the tailored outer skin. A micro-perforated foil lies on top of the composition and ensures a smooth surface and a homogeneous suction of the boundary layer. The holes are about 50μm due to aerodynamic reasons [6] and done by etching what was found to be advantageous compared to other production methods by means of quality and reproducibility [5].

A tight mesh serves as second layer that is responsible for the suction velocity what determines the pressure distribution on the surface. The properties of the layer can be adjusted by varying the numbers of wires in the warp direction. Two additional meshes with larger aperture size are added to increase the mechanical strength and stiffness of the mesh-composite. All layers are joined by a diffusion welding process.

3 Aerodynamic design and TSSD layout

For the design process of the outer skin the properties of the tailored material have to be determined first. Especially the dependency of the suction velocity on the mesh configuration is of great interest.

The current design assumes that the leading edge is placed in a wind tunnel experiment. The expected surface loads were calculated using the DLR in-house code Tau at Ma=0.35 and validated with experimental data collected in previous tests. With this condition a pressure distribution was derived that has to be present at the outer skin in order to influence the boundary layer in a positive manor. By adjusting the second layer of the outer skin a defined pressure distribution can be realized since the flow resistance through the porous surface depends on the filling threads in this layer. Experiments were carried out to link a certain suction velocity to this layout. With the help of the large flow meter (LFM), a measuring unit for pressure loss characteristics of porous materials developed at the Institute of Aerodynamic and Flow Technology, a correlation between the pressure loss Δp and the suction velocity w_s was found [7].

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

A and B are constant factors for the specific tailored layup at ambient conditions and listed in table 1, $\frac{\mu_s}{\mu_0}$ and $\frac{\rho_s}{\rho_0}$ are the viscosity and pressure ratios, respectively. With equartion (1) in mind the aim was to find a chordwise distribution of

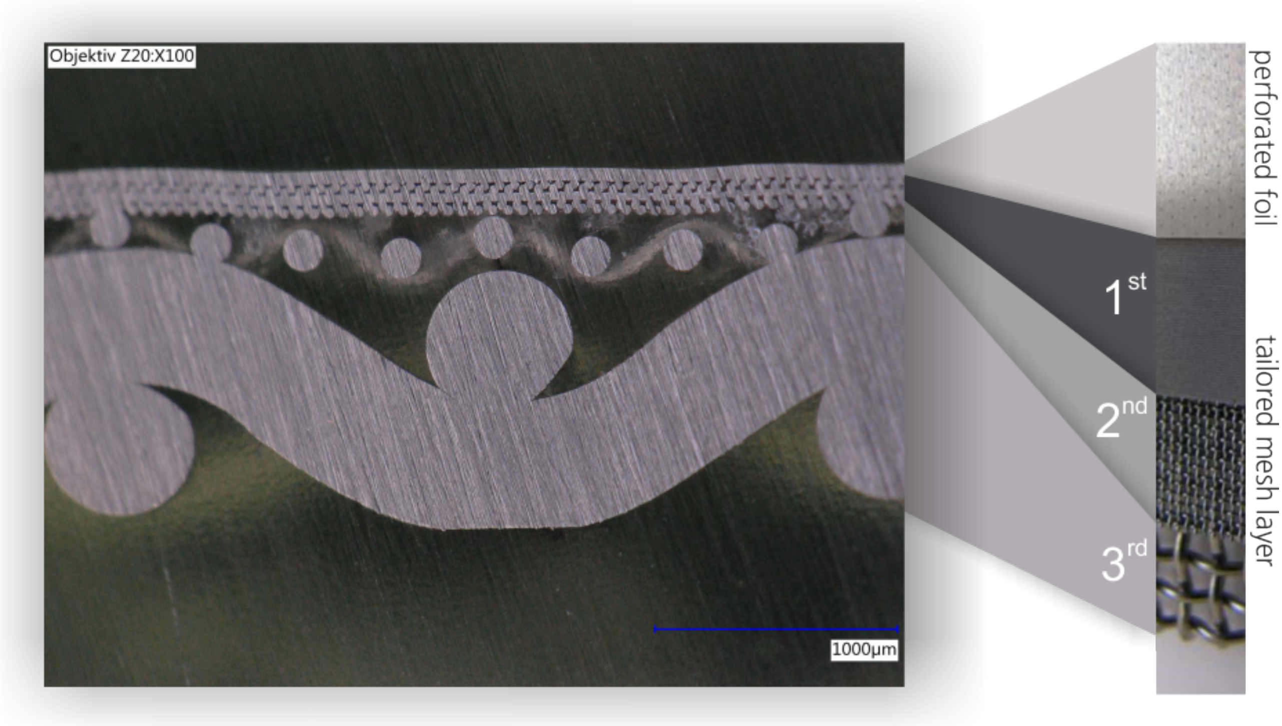


Fig. 1 Multilayered outer skin

sample	A [Pa s/m]	B [Pa s^2/m^2]	P_0 [Pa]	T_0 [$^\circ K$]
DTW-M1	−31446.44	−61330.57	100000	295.32
DTW-M2	−26619.43	−43726.50	99970	295.65
DTW-M3	−25256.73	−42670.90	100340	293.65
RPD-M1	−18173.74	−35870.69	100260	294.10
RPD-M2	−17066.83	−30474.64	100215	294.47
RPD-M3	−18363.73	−35981.51	99890	295.65

Table 1 Coefficients for equation (1)

the porous material by adopting the constants A and B to create a favourable pressure distribution that matches the target profile.

Diagram 2 shows the ideal suction velocity approximated with the available tailored skin configurations. The highest suction velocity is present at the nose ($s/l = 0$) and decreases with the profile depth till the end of the suction system at about 20% ($s/l = 0.2$). As can be seen the desired pressure can be reached using the available mesh configurations.

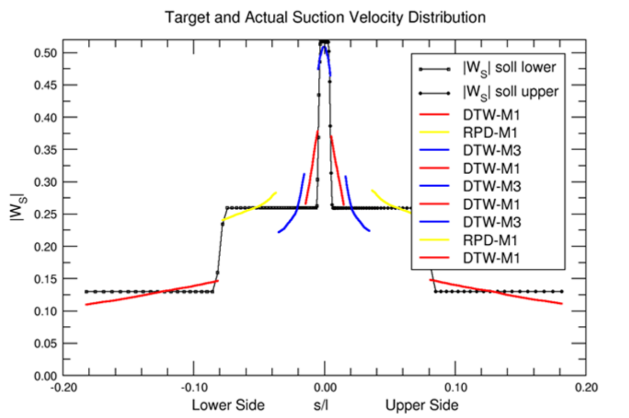


Fig. 2 Suction velocity profile approximated with different tailored skins

4 Structural Design

In addition to the aerodynamic requirements the considered leading edge has to fulfil structural demands. Beside static loads dynamic impacts,

(a) Sketch of the current design

(b) First demonstrating structure

Fig. 3 TSSD Buildup

for example due to bird strikes, are main criteria for the design process. The impact energy has to be absorbed or deflected to prevent damage of the underlying, load carrying and primary structure. Another important aspect is the functionality of the HLFC-system. It is very likely that the small holes will get contaminated by particles in the air like dust or insects. For that reason an easy service and maintenance routine is favorable and the joining components as well as the whole part have to be constructed to that. The suction area should be sealed so that the boundary layer is only influenced where it has a positive impact on the aerodynamic. The state of the art suction technology uses a great number of individual chambers to create a specific pressure distribution on the surface what leads to design restrictions in the underlying structure and influences the arrangement of the joining elements. With the TSSD design it is possible to adjust the pressure distribution directly in the outer skin and no extra specification to the underlying structure has to be done.

4.1 Structural Design Concept

The basic build of the TSSD design consists of three main components as shown in figure 3(a): The outer skin, the splitter and ribs/stringers. In order to deal with the dynamic loads a splitter-concept was applied [8]. The splitter has the task to deflect the dynamic loads so that they are not absorbed by the structure. The outer skin is connected to the splitter by ribs that can be arranged arbitrarily in the space between those two components. While the outer skin is made of steel, CFR-PEEK is used for the splitter and the ribs.

4.2 Demountable Leading Edge

Aerodynamic and manufacturing challenges are tasks to cope with. But also the service and maintenance ability is an essential point that has to be considered especially because the operational capability of the HLFC system is vulnerable to small damages and contaminations of the outer skin. They might block the small holes in the perforated foil what can influence the suction velocity and by that reduces the efficiency of the system. For that reason a demountable concept for the TSSD method plays an important part in the design process. To realize an easy handling of the parts, screws are connected to the outer skin by laser welding. These are connected to the ribs by suitable fasteners, while the splitter is also attached to the rib by a detachable joint [7].

For the HLFC system to work efficiently the plenum has to be sealed to make sure that the boundary layer is only influenced at defined regions and the required energy is kept to a minimum. A flexible demountable sealing system has to be found.

4.3 Sealing Concept

The porous outer skin is permeable in all directions thus a leakage will occur on the edge of the suction part. To increase the efficiency of the system by reducing the pump energy the outer boundary of the tailored skin should be sealed with a suitable material. If the whole leading edge component is sealed and manufactured as a closed system it is possible to check the functionality of the system before the part is actually integrated into the final structure. Since the outer skin is made of different layers and each layer is permeable (except for the perforated foil), a sealing material has to be found that infuses the whole skin. In order to find a suiting material, different tests were carried out. One major property that determines the material behavior in the manufacturing process is the viscosity. Different silicones were tested in a viscosity range between 3500 mPa and 200000 mPa. In that phase the qualification of the material for flight condition was not taken into account since the aim was to test a broad range of different viscosities. An elastic material was chosen in order to remain the possibility to apply the sealing material before the outer skin is formed into its final shape. Silicones were found to able to withstand the bending process to a certain degree without losing the sealing ability.

Small samples of the tailored outer skin were made and each specimen was treated with a different silicone for one third of its length as shown in figure 4. The treated part of the probe was put under a vacuum bag and connected to a vacuum pump. A second vacuum bag sealed the front part to measure a reference value for each specimen. The experimental setup is shown in figure 5. First the pressure in the closed setup was measured than the front part was opened and the difference between the closed setting and the actual sealed probe was compared. The difference between the first measurement and the second one is an

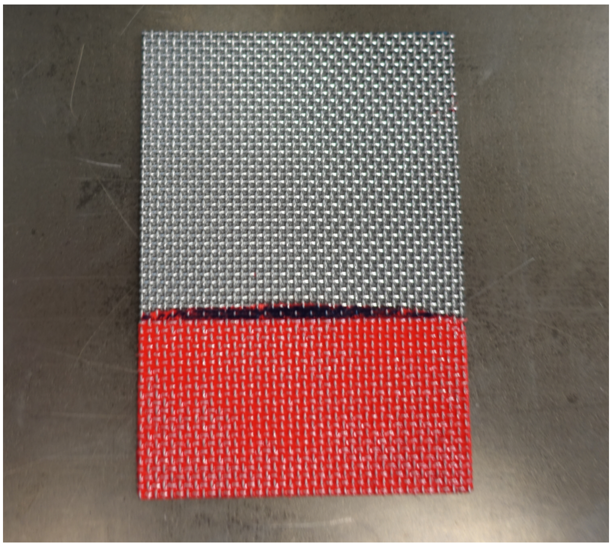


Fig. 4 Tailored skin sealing specimen

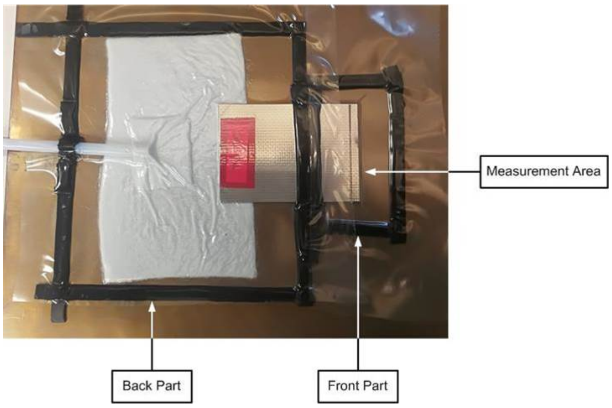


Fig. 5 Experiment setup

Fig. 6 polished specimen

indicator for the quality of the sealing material.

Nearly all materials, except for the one with a very high viscosity showed good sealing properties in the experiment with differences of about 5 mbar compared to the completely sealed case. For each probe a polished micrograph section was done. It could be examined that the low viscosity material was able to infuse the tailored skin very good by reaching up to the perforated foil as can be seen in figure 6. Only the high-viscous silicone left a few holes in the narrow second layer. With these results a viscosity between 10000 and 50000 mPas seems to be favourable for this application in will be further investigated.

4.4 Optimizaiton Process

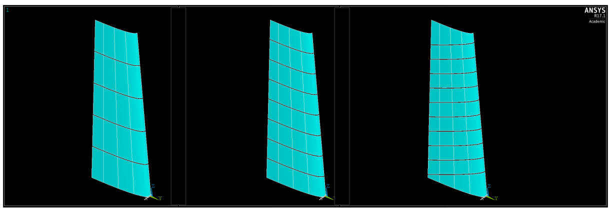
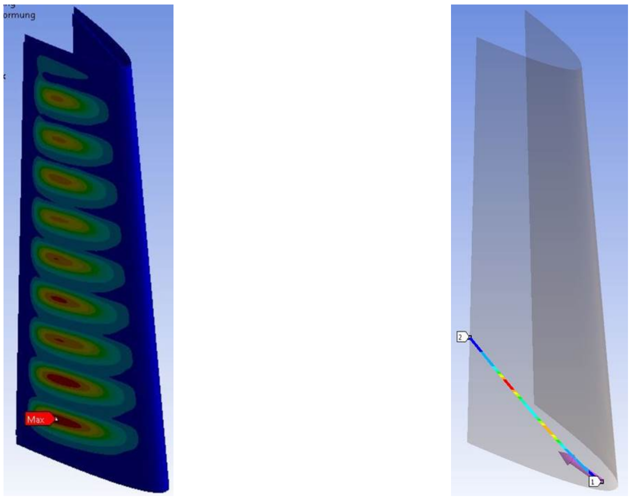


Fig. 7 Different rib arrangements

Due to the novel TSSD design the suction velocity on the porous surface does not constrain the underlying structure. Various arrangements of the supporting elements are feasible to create a lightweight structure. As described earlier a splitter-design was chosen for the TSSD-leading edge system consisting of the outer skin, ribs or stringers and the splitter to absorb/deflect the dynamic loads. The geometry of the outer skin and the splitter are considered to be fixed and will not be modified any further. That leaves the optimization process to the ribs that connect the outer surface to the splitter and ensure the aerodynamic shape. With the aim to find an efficient arrangement of the ribs an optimization tool was developed. No specific HLFC design criterion is elaborated so far that indicates the functioning of the system, for that reason the waviness criterion for natural laminar flow profiles is used. It gives a limit to the maximum deformation of $2mm$ and a maximum mean slope of 0.005. The load cases of a wind tunnel experiment were used with a 0°, 2° and 6° angle of attack.



(a) Deformation of the outer skin

(b) Spline with max. slope

Fig. 8 FEM results: max. deformation and max. gradient

First the boundary conditions, design space, design variables and constraints are defined while suitable ranges for the design variables are chosen. The geometry is made of by a parametric model that is adjusted each iteration. Three different parameters can me modified in the model: the thickness and the number of ribs as well as the angle to the flow direction. The boundary conditions, for example the pressure distributions,

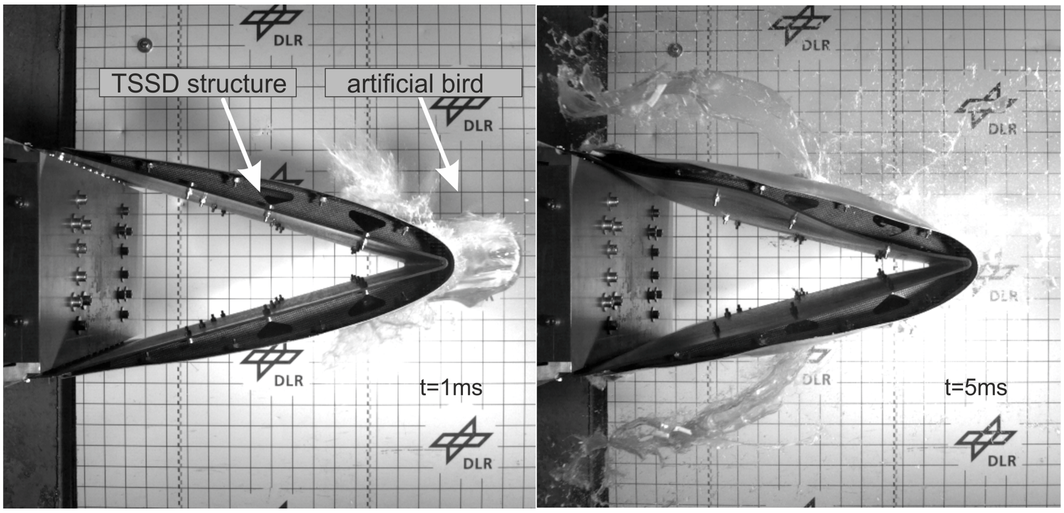


Fig. 9 TSSD bird strike test

are adapted to the geometry and converted to input files that are used for further processing. In the second step a FEM-calculation is carried out using Ansys and the max. gradient and the max. deformation is analyzed, see figure 8(a) and 8(b). The next iteration starts by generating a new rib design, as sketched in figure 7.

For the considered case a number of 10 ribs was found to be needed in order to meet the requirements. The optimization routines were developed using python and the Ansys Parametric Design Language (APDL).

4.5 Bird Strike Capability

The leading edge prototype was pre-sized and tested with the bird-strike requirements given by FAR 25.631. This can be translated into an impact of a bird of 3.6 kg (8 lbs) at a velocity of approximately 185 $\frac{m}{s}$. The prototype design which was finalized incorporated a mesh-based outer skin which was supported by horizontal ribs. These were connected to the V-shaped splitter on the inside as shwon in figure 3(b). Due to the restrictions by the size of the physical prototype production to a length of 800 mm, the test has been performed with a perpendicular impact where the horizontal ribs were oriented perpendicular to the leading edge. The impactor used for the test was a reinforced artificial bird [9] This type of artificial or substitute bird is gelatine based and comprises a plastics reinforcement besides the tissue simulant. This built-up was chosen to maintain the shape of the impact during the impact test. Tests with artificial birds have shown unreproducible deformations [10] which apparently origin the acceleration in a gas gun, the release from a so-called sabot followed by a free flight between the gas gun's muzzle and the impact on the structure [11].

The experiment showed good results considering the impact capability of the TSSD segment. Although a part of the bird tore a hole in the outer skin the splitter was able to deflect the impact and no underlying primary structure was damaged.

5 Conclusion and Outlook

Many attempts were made in the last decade to actively influence the boundary layer with the aim to save fuel. State of the art HLFC-Systems use a multiplicity of sealed chambers to generate the desired pressure distribution on the surface. That comes with a lot of restrictions and leads to a more complicated design and manufacturing process.

The TSSD-method gets rid of these structural restrictions by transferring the adjustment of the suction velocity directly into the outer skin. New design opportunities are feasible that way to cope the increased weight that has to be implemented due to the suction system. Because of the complexity of the system a detachable design was considered so that service and maintenance tasks can be executed more easily.

Further investigations will consider the blocking effect of the underlying structure on the outer skin to ensure that the ribs won't manipulate the suction velocity on the surface. Another task is the upscaling of the manufacturing process especially for the tailored outer skin. The TSSD-system shows promising results so far and it is planned to validate a real scale leading edge in a wind tunnel experiment.

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