Research on sailplane aerodynamics at Delft University of Technology. Recent and present developments.

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Summary
The paper consists of two parts.
Part one describes the findings of recent aerodynamic developments at Delft University of Technology, Faculty of Aerospace Engineering, and applied in high-performance sailplanes as illustrated by the Advantage, Antares, Stemme S2/S6/S8/S9 family, Mü-31 and Concordia (Chapter 1). The same technology has been applied in the aerodynamic design of the Nuna solar cars as illustrated by the Nuna-3 (Chapter 2). Part two describes results of ongoing research on boundary layer control by suction, a beckoning perspective for significant drag reduction (Chapter 3).

1. Recent research on sailplane aerodynamics

1.1. Introduction
The speed polar of a high-performance sailplane, subdivided in contributions to the sink rate of the wing, fuselage and tailplanes, Figure 1, illustrates that the largest contribution is due to the wing; at low speed due to induced drag and at high speed due to profile drag\(^1\).

![Figure 1 Contributions to the speed polar of the ASW-27](image)

Hence, improvements have been focused on these contributions, followed by the fuselage and tailplane drag, in particular at high speed. These improvements will be illustrated by examples of various new sailplane designs. It should be pointed out, however, that each new sailplane design incorporates improvements similar to those presented here for the individual sailplanes.
1.2. Induced drag
Induced drag has been minimized by optimizing the wing planform with integrated winglets, as illustrated by the wing of the Advantage shown in Figure 2a. The Advantage is a new Standard Class high-performance sailplane with shoulder wing, Figure 3, being built by Sailplanes Inc. in New Zealand.

![Figure 2a Planform and lift distribution of the Advantage wing in comparison with Munk's optimum lift distribution for minimum induced drag](image)

Winglets can be optimized at one lift coefficient only, as indicated in Figure 2a where the winglet has been bent down to show the actual lift distributions and the optimal lift distribution according to Munk’s third theorem. But Figure 2b shows that the absolute minimum induced drag can be realized within 1% at all lift coefficients. Besides, the winglet airfoils have been designed for low profile drag in their operational region of lift coefficients, obtained by 100% laminar flow on the lower surface and 50% on the upper surface. In addition, ample reserve to separation in case of yaw has been applied, in particular at low speed when circling in thermals.
1.3. Profile drag

Profile drag depends on the extent of the laminar boundary layer on the upper and lower surfaces and on airfoil thickness. As an example, the 12.7% thick airfoil with camber changing flap of 14% chord, applied as main airfoil in the Antares wing, is presented.

The Antares is a new 20 m-span high-performance sailplane with retractable electric engine, Figure 4. The very efficient 42.5 kW DC/DC brushless outside rotating engine and the large slowly rotating propeller enable starting and climbing silently with 4.4 m/s to a maximum altitude of 3,000 m. Usually, at an altitude of about 500 m the engine is retracted and ample power is available to extend the engine and fly home when thermals are weakening. Lithium-ion batteries are placed in the inner wing and water ballast tanks – to increase the wing loading - in the outer wing.

Figure 2b  Induced drag factor of the Advantage wing in comparison with Munk's minimum induced drag factor

Figure 3  The Standard Class high-performance sailplane Advantage of Sailplane Inc., New Zealand
The wing airfoil has laminar flow up to 95% of the chord on the lower surface at the high-speed zero-degree flap deflection, and up to 75% of the chord on the upper surface at the low-speed 20 degrees flap deflection, as indicated by the pressure distributions in Figure 5. The upper and lower surface flap gaps have been sealed by flexible mylar strips. This enables the boundary layer on the lower surface to remain laminar beyond the flap hinge position at the zero-degree flap deflection up to 95% chord where transition is artificially forced by zigzag tape. On the upper surface the sealing prevents low-pressure peaks and subsequent steep pressure gradients on the flap at 20 degrees deflection, thus postponing separation. Consequently, the profile drag is very low over a large range of lift coefficients, as shown by the measured characteristics in Figure 6.

Full laminar flow on the lower surface cannot be realized at low lift coefficients and high Reynolds numbers due to the adverse pressure gradient needed to reach the overpressure at the trailing edge. And an increase of the laminar flow extent on the upper surface leads to a steeper pressure gradient in the rear part, which in turn enhances flow separation and a loss of lift beyond the upper boundary of the low drag bucket. This causes unfavorable flying qualities in thermals. This example shows that further drag reduction of airfoils by conventional means is hampered, this being the reason for the present research on boundary layer suction as described in the second part of the paper.

Figure 4  The Antares 20 m span high-performance sailplane with retractable electric engine.
Figure 5  Pressure distributions of airfoil DU97-127/15M at 0, 10 and 20 degrees flap deflection

Figure 6  Measured aerodynamic characteristics of airfoil DU97-127/15M at various flap deflections and Reynolds number 1.5 * 10^6
1.4. Fuselage drag
Fuselage drag depends mainly on fuselage thickness, contraction behind the cockpit, and streamline shaping. Fuselage frontal area should be minimal. Contraction behind the cockpit – and the corresponding pressure gradient - is limited because of flow separation when the boundary layer on the fuselage is completely turbulent, for instance when flying in rain. Streamline shaping by fitting the fuselage shape to the streamlines produced by the wing minimizes cross-flow effects. For an undisturbed boundary layer development, continuity of curvature is required in flow direction. This is guaranteed by deriving the top, bottom, and line of largest width from airfoil shapes, and using Hügelschäffer curves (deformed ellipses) for the fuselage cross-sections.

A remarkable finding is that the cockpit length can be increased by 0.3 m without any drag increase, as illustrated by the accumulative development of the drag coefficient on a rotationally symmetrical body in the Figures 7a and 7b. Transition occurs at 33% of the original fuselage length, and the total drag is found at the tail. This result offers the possibility for improved crashworthiness measures as a longer crumbling nose cone and keeping the pilot’s feet out of this zone. These features have been implemented in the design of the fuselages of the Advantage and Antares.

![Pressure distribution on a fuselage with cockpit extension](image)
The aerodynamics of a wing-fuselage combination is complicated\textsuperscript{3}. As sketched in Figure 8, main flow effects are, at an increasing angle of attack, an additional increase of the angle of attack in the wing root region due to cross-flow of the fuselage named alpha-flow, resulting in viscous flow effects as the forward shift of the transition position on the wing and, if the laminar airfoil is not modified, separated flow at the rear of the wing root. At a decreasing angle of attack, an additional decrease of the angle of attack occurs in the wing root region causing transition to move forward on the lower surface of the wing. Another viscous flow problem is the separation of the turbulent boundary layer on the fuselage in front of the wing root due to the steep adverse pressure gradient towards the stagnation pressure on the wing root leading edge, and the resulting vortical flow system on the fuselage around the wing root.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7b}
\caption{Development of the drag on a fuselage with cockpit extension}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{Alpha-flow effect (left) and viscous flow effects (right) on a wing-fuselage combination}
\end{figure}
Figure 9  Oil flow patterns on the wing lower surface (upper picture), wing upper surface (middle picture) and fuselage of a high-performance sailplane windtunnel model
Figure 9 shows flow patterns, visualized by fluorescent oil in UV light, on the wing and fuselage of a high-performance sailplane windtunnel model. The change of friction at transition and zero friction at separation are depicted in the oil flow. The curved transition lines on the wing due the alpha-flow effect, and the separated flow on the wing-root upper surface are clearly visible. Zigzag tape, intended to trip the laminar boundary layer, is located in the turbulent boundary layer now and produces small vortices as indicated by the oil traces. Transition on the fuselage and the separation line around the wing root are clearly visible as well. In addition to these friction and pressure drag producing viscous flow effects, the circulation distribution of the wing-fuselage combination produces more induced drag than the wing only. The following examples illustrate how these problems have been tackled.

The Stemme S2/S6/S8/S9 family of gliders, soaring motor-gliders (engine behind the cockpit, retractable propeller in the nose cone) and touring motor-gliders (fixed propeller), has the same side-by-side two-seater cockpit configuration and fuselage junction, Figure 10. Two wings have been designed, one with 18 m and one with 20 m span, which have identical inner parts up to 9 m span. Both wings have winglets, but they have been omitted in the present case focused on wing-fuselage flow problems.
Flow problems due to the large fuselage contraction below the wing could be overcome due to the favorable effects of the shoulder wing location on the pressure distribution. From 2.5 m inwards the laminar airfoil of the wing has been modified and twist has been applied. In this way the boundary layer on upper and lower surface could be kept laminar as far as possible in chord direction and as close as possible to the fuselage, and the loss of lift due to the presence of the fuselage could be compensated. Next to the fuselage the airfoil is suitable for turbulent flow, and the chord is extended to lower the pressure gradient and postpone separation. Figure 11 shows streamline patterns colored corresponding to the boundary layer shape factor; the sudden change in color marks transition. The touring motorglider Stemme 6 made its maiden flight in November 2006.

Figure 11  Streamline pattern on the wing-fuselage combination of the Stemme family
The Concordia is a new single seat Open Class sailplane with 28 m wing span designed for a maximum take off weight of 850 kg, Figure 12. The relatively small wing area (high aspect ratio of 57.3) and water tanks in the wing, fuselage and tail enable the wing loading to be varied from 40 kg/m$^2$ to 62 kg/m$^2$, thus improving cross-country performance from weak to strong thermal conditions.

Figure 12 Three views of the single seat Open Class sailplane Concordia

Figure 13 shows the 14 airfoils applied in the junction, wing and winglet, taking into account respectively the turbulent flow in the junction, the required circulation on the whole fuselage-wing-winglets combination, and the local Reynolds numbers; all focused on low drag.

Figure 13 Position of the 14 airfoils applied in the wing of the Concordia
In order to reduce construction work on the fuselage, the front part as far as the end of the wing-junction, including the wing attachment pins, has been taken from the ASW-27. The position of these pins and the requirement to fit the fuselage perfectly to the streamlines produced by the wing at the high-speed lift coefficient of 0.3, Figure 14, necessitated an increase of the wing chord towards the fuselage and twist between the fuselage and 1 m span position. The twist is applied by rotating the wing around the hinge line of the flap, which has to remain straight. In order to realize the proper lift distribution for minimum induced drag, the flap is twisted as well and reaches up to the fuselage. Similar to the Stemme design, the airfoils in the region up to 1 m span are modified in order to keep the boundary layer laminar as far as possible in chord direction and as close as possible to the fuselage, both at high-speed and low-speed flap deflections, and a trailing edge fairing is applied at the wing root to lower the pressure gradient. Figure 15 gives an impression of the complicated wing-fuselage junction.

**Figure 14** The fuselage of the Concordia has been fitted to the streamlines produced by the wing at \( C_l = 0.3 \).

Performance calculations indicate a best glide ratio of 72 at wing loading 40 kg/m\(^2\) and 75 at wing loading 62 kg/m\(^2\), which corresponds with a glide angle of only 0.8 degrees and 0.76 degrees respectively. At the high wing loading the sink rate is only about 1 m/s at a flight speed of 200 km/hr. The Concordia is being built in USA by Dick Butler, Tullahoma, USA. The fuselage and tailplanes are completed and the wing is currently being built in accurately machine-milled moulds.
The Mü-31 is a sailplane prototype of the FAI 15-metre Class, developed by students of the Akaflieg München, aiming at an improved wing-fuselage design, Figure 16. To reduce costs and time, the cockpit, outer wings and tailplanes of the ASW-27 are used, whereas the center section of the wing and the fuselage contain the new approach of wing-fuselage design. The main goal of this new geometry is the realization of a high-wing configuration that has several benefits. Compared to conventional mid-wing configurations less boundary layer material coming from the fuselage flows over the upper surface of the wing-fuselage combination. Therefore it is expected that separation will be postponed, allowing for better low flight speed capabilities. Another feature is the contraction of the fuselage below
the wing, leading to a reduced wetted surface of the tailcone. While in midwing configurations the horseshoe-vortices at the wing root affect the flow over the tailcone, at the present pylon-like wing configuration the vortices leaving the pylon do not touch the fuselage.

![Image](image.png)

**Figure 16** The FAI 15-metre Class sailplane Mü-31

At first, an extensive theoretical and experimental investigation was made of three similar high-wing-fuselage configurations where the wing had respectively a straight inner part, a twisted inner part (to compensate for the loss in lift due to the fuselage), and a twisted inner part plus airfoil modification towards the fuselage (suited for turbulent flow). This study revealed the strong effect of respectively the twist on induced drag, the airfoil modification on profile drag, and the contraction of the pylon on flow separation. Based on these findings a new fully integrated high-wing-fuselage combination has been designed which has an induced drag almost equal to the induced drag of the wing only, laminar flow on the wing as far as possible in chord direction and towards the fuselage, and no boundary layer separation on the pylon. Windtunnel tests with a carefully milled model, Figure 17, substantiated the intended improvements. The structural design of the Mü-31 is completed and the moulds for the wing center section and fuselage are currently being milled.

A new theoretical method for the design of a leading edge fairing has been developed and experimentally verified. Such a fairing avoids flow separation on the fuselage in front of the wing root and the subsequent vortical flow system around the wing root. In addition, it causes the approaching turbulent boundary layer to relaminarize rapidly on the fairing. This method has been applied for the first time at the vertical tailplane-tailboom junction and at the wing-root-junction of the Advantage, Figure 18. Note that the streamlines on the fuselage continue over the fairing, indicating that separation doesn’t occur. The code is not able to calculate relaminarization, however.
1.6. Tailplanes

New horizontal tailplane airfoils have been developed with laminar flow on the upper and lower surfaces up to the elevator, where artificial transition is forced by zigzag tape. Along with realizing low drag, the challenge is to postpone the loss of lift due to separation at high elevator deflections, as occur in cases of an emergency such as a cable break.

Three-dimensional effects due to the tip vortices, which appreciably reduce the angle of attack (and lift coefficient) at low aspect ratio wings, are helpful in this respect as will be shown in the next example.

Figure 19 presents the calculated characteristics of the airfoil applied in the vertical tailplane of the Antares. The figure on the right shows that laminar
flow is present up to the 40% depth rudder, where transition is fixed by zigzag tape except when natural transition occurs earlier. The figure on the left indicates that separation on the rudder, deflected at 15 degrees (upper lift curve), starts at an angle of attack of –2 degrees. In practice however, due to the effects mentioned at the low-aspect ratio vertical tailplane, the local lift coefficient is much lower than the two-dimensional value, and calculations show that separation of the rudder starts at a yaw angle of about 5 degrees. Due to the endplate effect of the horizontal tailplane and the tipeffect at the lower end, separation starts at the upper end of the rudder and progresses downward.

Figure 19  Calculated aerodynamic characteristics of airfoil DU99-126/40MOD at Reynolds number $1.5 \times 10^6$

Similar effects occur at a larger rudder deflection; at a 25-degrees deflection the flow on the rudder of the two-dimensional airfoil starts to separate at an angle of attack of –5 degrees, but in the three-dimensional case the flow remains attached up to a yaw angle of 1 degree. Figure 20 illustrates the situation at a yaw angle of 2 degrees; flow separation occurs on the upper part of the rudder as indicated by the end of the streamlines. The vortices trailing off the ends of the horizontal and vertical tailplanes are clearly shown. Calculations at turning flight conditions substantiate that the flow on the rudder is always attached.
2. Application to solar powered cars

The Nuna 1, 2 and 3 are solar powered cars developed by students of the TU Delft for the World Solar Challenge. This is a race, held in Australia every second year since 1987, covering a distance of about 3000 km from Darwin to Adelaide. The Nuna 1 won this race in 2001 with an average speed of 92 km/hr, the Nuna 2 won in 2003 with 97 km/hr and the Nuna 3 won in 2005 with an average speed of 103 km/hr. For the aerodynamic design of these cars, the same ideas and tools have been applied as for the design of sailplanes. For example, the body of the Nuna 3 and front wheel fairings, Figure 21, could be viewed as a wing with a small span and a large chord depth, with winglets. Low drag is realized by long extents of laminar flow on the upper and lower surfaces. The wheel fairings are small wings with laminar flow airfoils as well. The front fairings are designed to suck in driving direction at side-wind conditions, like the sail of a sailboat, thus reducing the drag in driving direction. The low pressure on the inner side of the fairings is felt on the lower surface of the body as well and would cause a bump in the pressure distribution, which limits the extent of the laminar flow. This bump has been eliminated by dents in the lower surface, Figures 22 and 23. The oil flow pattern on the upper and lower surfaces, shown in Figures 24 and 25, indicate laminar flow up to and around the cockpit and up to the rear wheel fairing respectively. The measured drag coefficient of 0.0899 at a frontal area of 0.785 m² results in the very low drag area of 0.0706 m². This is slightly lower than the drag area of an A4 paper size perpendicular to the flow.
Figure 21  The solar powered car Nuna 3

Figure 22  Pressure distribution on the lower surface of the Nuna 3, allowing laminar flow up to the rear wheel fairing (not present)
Figure 23  The laminar airfoil shape applied in the Nuna 2, and cross sections of the Nuna 3. Cross section 0.000 is the symmetry plane, cross section 0.5994 is next to the front wheel fairings. Vertical scale is blown up.

Figure 24  Oil flow pattern on the upper surface of the Nuna 3 windtunnel model.
3. Boundary layer suction

The goal of boundary layer suction is:
• to reduce drag by keeping the boundary layer laminar and attached up to the trailing edge, and/or
• to increase lift by keeping the turbulent boundary layer attached.

As illustrated in Figure 26 the drag of an airfoil with boundary layer suction - in the present case on the rear upper surface - is composed of wake drag, sink drag and equivalent suction drag. Wake drag is due to the boundary layer development on upper and lower surfaces forming the wake, and is composed of friction drag and pressure drag. Sink drag is created by the momentum loss of the sucked air brought to rest in the wing, and can be reduced to zero again by blowing this air out backwards with a velocity equal to the flight speed. The equivalent suction drag implies the power needed to bring the sucked air $Q$ in the wing back to ambient pressure $p_\infty$ and flight speed $V_\infty$.

The principle of blowing the sucked air out backwards in order to reduce the sink drag, no matter the power source (solar cells, wind turbine, batteries), can be interpreted as thrust, which is not allowed according to the present FAI definition of a sailplane. However, as will be shown, the improvement in sailplane performance due to boundary layer suction is so large that it would be unfair to compete with such a sailplane in the existing classes. Hence a new class has to be defined, and in doing so the
International Gliding Commission of the FAI should take new technological possibilities into consideration.

A breakthrough for the application of boundary layer suction is the possibility to produce many tiny holes (0.1 mm diameter, every 1 mm) in carbon fiber laminate by micro abrasive air jetting, an adapted version of sandblasting. This new and cheap technology, developed at Delft University of Technology, is based on the erosion of a mask-protected carbon laminate by a high-velocity beam of abrasive powder (bulk material), blown by pressurized air through a nozzle. The geometry of the mask, easily produced of photosensitive polymeric film, determines the hole pattern. A blasting cabinet with a computer controlled traversing system has been built, Figure 27, and research is going on to further optimize this technology for use on a large scale.

While a minimum amount of suction is required to keep the

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**Figure 26**  Drag contributions in case of boundary layer suction

**Figure 27**  The blasting cabinet for micro abrasive air jetting, with traversing system on top
boundary layer laminar and attached, there is an upper limit as well, because strong suction produces vortices that originate at each hole and become unstable, acting like a turbulator. In order to determine this suction limit as well as the pressure loss of the suction holes, windtunnel tests have been carried out with a model especially designed for this purpose and equipped with a suction sandwich skin as shown by the dark area in Figure 28.

As shown by the expression for the suction power, minimum suction power is realized when the required minimum suction flow rate $Q$ is brought back to ambient pressure $p_\infty$ and flight speed $V_\infty$. The required minimum suction flow rate is determined by the suction distribution in chordwise direction required to keep the boundary layer laminar and attached. This suction distribution is realized with a specific pressure difference between the outer and inner sides of the porous outer skin, and since the outer pressure varies in chordwise direction, the inner pressure should vary too. When this suction air is finally brought back to ambient pressure and flight speed, the ideal minimum suction power is obtained.

In practice, the minimum suction distribution can be realized by a special layout of the suction sandwich on top of the structural sandwich, Figure 29. The air is sucked through the perforated outer skin, flows in forward direction through a perforated folded core and finally through throttling holes into the inner space of the wing, where the pressure is controlled by

*Figure 28  Windtunnel model for boundary layer experiments in the interchangeable test section of the Low Speed Low Turbulence Windtunnel of TU Delft*
a pump. The suction sandwich is divided in buffers and an imperforated wall of the folded core separates the buffers.

The suction sandwich can be compared with corrugated cardboard with many tiny holes in the upper skin, larger and fewer holes in the folded core and even larger and fewer holes in the lower skin. The folded core is a new core material developed at the Institut für Flugzeugbau of the TU Stuttgart. The channel type structure enables cleaning the inner structure when pollen and dirt are sucked into the suction sandwich.

While the minimum suction distribution at a particular flight speed can be realized in practice, the ideal minimum suction power cannot be realized because all the suction air has to be brought back from a certain inner pressure - and not an inner pressure that varies in chordwise direction - to ambient pressure. This inner pressure has to be slightly lower than the lowest outer pressure on the airfoil. In addition, the layout of the perforations in the suction sandwich can be optimized for one flight speed only.

When suction would be applied on the rear upper surface of a Standard Class sailplane wing, Figure 30 shows the ideal minimum suction power and the real suction power (per square meter wing area) for the best suction sandwich layout with 2 buffers. Although the actual power is about twice the ideal one, the power required is still very low, as indicated by the solar power datum used for the design of the solar powered glider Icare-2. Figure 31 shows the dramatic reduction in profile drag and the increase in lift due to suction. At lift coefficients below 0.9 suction keeps the boundary layer laminar, thus reducing pressure drag and friction drag. At lift coefficients above 0.9 natural transition occurs in front of the suction area and the same suction distribution needed for laminarization is applied to postpone separation of the turbulent boundary layer, thus increasing the lift. Finally, Figure 32 shows the corresponding enormous improvement of the speed polar and glide ratio.
Figure 30  Ideal minimum suction power and the real suction power

Figure 31  Calculated aerodynamic characteristics without and with boundary layer suction
Research on boundary layer suction is going on in an effort to solve the remaining problems step by step, and to develop an airfoil specially designed for boundary layer suction, because the improvement in performance is a very beckoning perspective.

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5. References