SAILPLANE FUSELAGE AND WING-FUSELAGE JUNCTION DESIGN

Presented at XXV Ostiv Congress - S. Auban (France) 3-11 July 1997

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Abstract

This paper deals with an investigation on sailplane fuselage and wing-fuselage junction aerodynamics. In the first part of the paper a method to evaluate fuselage drag has been used to evaluate the influence of some basic shape parameters on drag. A three-dimensional panel code is used to solve the potential flow field and the boundary layer is evaluated along some streamlines on the body, leading to an approximate value of the drag coefficient (for non-axisymmetric bodies).

The influence of an increase of cockpit lenght and height (which is important in view of crashworthiness measures), as well as that of contraction on fuselage drag has been investigated. The lenght of a typical sailplane fuselage cockpit has been increased by about 0.2 m. It will be shown that such an increase of fuselage lenght does not lead to any sensible drag increase.

While an increase of cockpit lenght has no effect on drag, the effect of an increase of fuselage height is unfavourable; an increase of fuselage height of 10% leads to an increase of fuselage drag of about 13%.

The fuselage contraction, an efficient way to reduce drag, has to be limited to a certain value to avoid separation of the turbulent boundary layer.

The second part of the paper presents the design of a new high performance sailplane wing-fuselage junction. An inverse 3D panel code and an optimization procedure have been used to design the junction.

The laminar wing airfoil has been changed towards the fuselage in order to preserve the laminar flow pressure distribution as far as possible up to the turbulent corner flow, where the target pressure distribution is suitable for the turbulent flow conditions, in this way flow separation in the junction region is avoided.

Introduction

The aerodynamic design of sailplanes has been constantly improved since their introduction in the 1920's. The pure design of the new flight vehicles was soon accompanied by theoretical research and windtunnel testing.

An important step was made in the 1950's with the introduction of laminar flow airfoils. This new design technique required not only sophisticated design tools, but also rather high surface qualities.

A major part of the past research for sailplane drag reduction has been focused on the wing design, and expecially on airfoil design, see for istance [ref. 1].

The reduction of induced drag by using winglets has improved the climbing performances of sailplanes and research efforts are concentrated to find the right shape.

However, expecially at high speed conditions(low lift coefficient and then low induced drag), a good fuselage design is important to reduce the total drag.

It can be easily shown that, for a conventional sailplane with an aspect ratio of about 30, the fuselage drag is 6% of the total drag at a lift coefficient of 1.1 (best glide ratio) and increases to 20% of the total drag at a lift coefficient of 0.35 (high speed cruise condition), see fig. 1.

In this work a method to evaluate fuselage drag has been used to study the influence of a good fuselage shape design on drag reduction.

The method has been already applied for generic transport fuselage optimization [ref. 2].

The method was also applied [ref. 3] to optimize a general sailplane fuselage. It is evident ,then, that the fuselage shape has to satisfy to some specifications deriving from structural reasons or from space request for internal arrangements.

Taking in account all the geometrical constraints deriving from those considerations, an analysis of the influence of some shape parameters on sailplane fuselage drag has been done.

The influence of cockpit lenght and height increase on fuselage drag has been investigated for a general sailplane fuselage. It will be shown that while a fuselage "stretch" does not lead to any sensible drag increase, the increase of fuselage height can reduce sailplane performances.

The influence of fuselage contraction has been investigated. It will be shown that fuselage contraction can be a good way to reduce fuselage drag. New composite materials, while maintaining the same structural strenght of the original, larger tail cone sections, allow the reduction of tail cone area reducing at the same time the drag.

The second part of the work deals with the problem of wing-fuselage interference effects.

The design of the root wingsection has been a long lasting stepchild to saiplanes aerodynamicists; in fact they were well aware of the interference effects, but they lacked a proper knowledge of the complex physical models and their treatment with numerical design tools.

It was common to design the wing-fuselage junction by rather rough philosophies as "design-by-experience" and "design-by-well-proven-tradition".

Experimental work have been carried out [ref. 4] which gave a good comprehension of the flow phenomena at the wing-fuselage junction.

Nowadays numerical aerodynamic techniques are useful tools to design even complex threedimensional configurations.

The inverse design, extensively used for airfoil design (2D case), is now implemented in a three-dimensional panel code [ref. 5] and represents a useful tool in sailplane design. First by using an inverse design procedure, then by using an optimization technique, the airfoil shapes in the root area have been changed in order to achieve the desired pressure distributions. The wing-fuselage junction design of a new high-performance saiplane has then been carried out and will be presented.

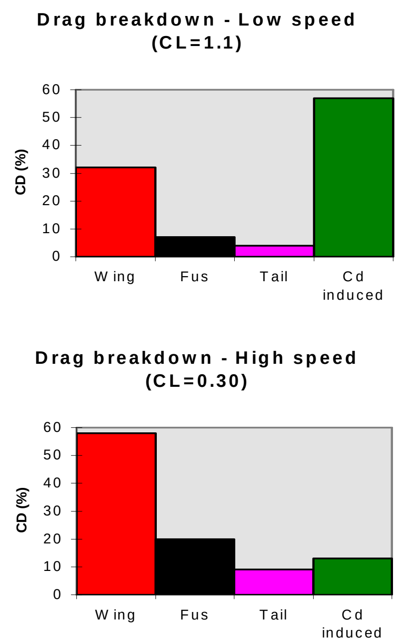

Fig. 1

Fuselage Aerodynamic Analysis

It is relatively easy to perform an aerodynamic analysis on a body of revolution. Once has been evaluated the potential pressure distribution on the body, viscous calculation can be performed, solving the boundary layer (b.l.) integral equations in the axisymmetric version. However extensively studies have been done [ref. 6] to show how classical correlations used to predict transition on airfoils are not accurate enough for high Reynolds numbers values (20÷30 millions, based on fuselage lenght *L*) which are characteristics of fuselages with 6÷7 meters or even higher lenght.

The e^n method in the approximate version proposed by Drela [ref. 7] has then been used to predict transition. The Drag coefficient for an axisymmetric body can be obtained using the formula proposed by Young [ref. 8] :

$$CD = \frac{2\pi}{S_{ref}} \left(r \cdot \theta \right)_T \left[Ue_T \right]^{\left(\frac{H+5}{2} \right)_T}$$

(1)

where CD is the drag coefficient, S_{ref} is a reference area (usually the maximum frontal area), r is the radius, θ is the b.l. momentum thickness, Ue is the inviscid external velocity and H is the b.l. shape factor. The subscript T indicates that all quantities are to be evaluated at the body tail (*x/L=1.0)*.

The drag coefficient can also be evaluated also by skin friction coefficient integration along the body surface. For high fineness ratio bodies (like usual sailplanes fuselages) this method lead to a value which is really close to the CD evaluated with (1), since pressure drag is negligible in these cases.

For general saiplane fuselages (non axisymmetric bodies) an approximate method has been used in order to perform viscous calculations. The potential flow pressure distribution can be evaluated on the fuselage (set at a fixed incidence and taking in account the wing influence, for istance) with a 3D panel method. It is then possible to perform viscous calculations along some streamlines along the body. The axisymmetric boundary layer can be evaluated along the upper and lower streamline (see fig. 2)

of the fuselage. The radius is considered as the mean value of the fuselage height, at each x-station, for both upper and lower streamline.

A drag coefficient can be obtained for both streamlines (eq. 1), leading to two values. The fuselage drag coefficient will be taken as the average of upper and lower values. It is clear that this represents an approximate method because the boundary layer on the fuselage is three-dimensional, and axisymmetric viscous calculations are not an accurate representation of a non-axisymmetric flow condition on a non-axisymmetric body. It is evident that the results are more and more inaccurate as the fuselage shape is far from an axisymmetric body.

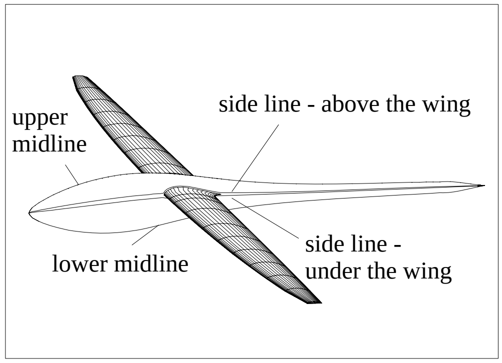

Fig. 2 : Streamlines along a fuselage

Viscous calculations can also be performed on other streamlines along the fuselage, as along side lines immediately above and under the wing (see again fig. 2).

Comparisons [ref. 9] with experiments have shown reasonably good agreement with experimental drag coefficients and transition locations not only in case of axisymmetric bodies, but also for some fuselages tested at Delft [ref.4].

Fuselage Design

In [ref. 6] a drag optimization of axisymmetric bodies has been performed at different Reynolds numbers. It has been shown that is possible to reduce the drag of a body of revolution through an extension of the laminar flow area both at low and high Reynolds numbers.

Anyway, in actual glider fuselage design, the "pure" low drag body of revolution is not practical and some modifications are needed to allow for the following design features:

- pilot visibility and internal arrangements
- effect of wing upwash and downwash for $CL \neq 0$
- minimum cross section compatible with pilot comfort
- tail cone structural strenght
- influence of the operative angle of attack range

An investigation has been done to check the influence of some shape parameters on fuselage drag.

<u>Effect of fuselage contraction</u>

The effect of fuselage contraction on fuselage drag has been investigated.

	CD num.	CD exp.[11]	*xtr/L* num.	*xtr/L* exp.
body 1	0.058	0.051	0.30	0.33
body 2	0.038	0.034	0.35	0.35
body 3	0.039	0.035	0.31	
body 4	0.40	0.038	0.29	0.31

Some axisymmetric bodies with the same maximum frontal area, but different contractions, were tested in Stuttgart by Althaus [ref. 10].

Fig. 3 shows the shape of the 4 bodies of revolution together with the relative pressure distributions. In table 1 the calculated and experimental transition locations and drag coefficients for the four shapes are presented. Body n. 2, 3 and 4 present a sensible wetted area reduction compared to that relative to body 1. The drag coefficient of body n. 1 is then higher than those relative to the other shapes. It is possible to see that body 3 and 4, with an higher contraction behind the section of maximum area than body 2, are characterized by higher drag coeffcient values. The explanation is that the contraction leads to a shift of the pressure peak toward the body nose, with a consequent transition location

advance. The effect of contraction is, in this case, a shift of transition location toward the nose. It is evident that this leads to a drag increase, although there is less wetted area and a skin friction coefficient reduction behind the cockpit (due to the steeper adverse pressure gradient).

We will show that through a well designed increase of contraction behind the cockpit (in such a way that transition is kept in the same position) is possible to obtain a sensible fuselage drag reduction.

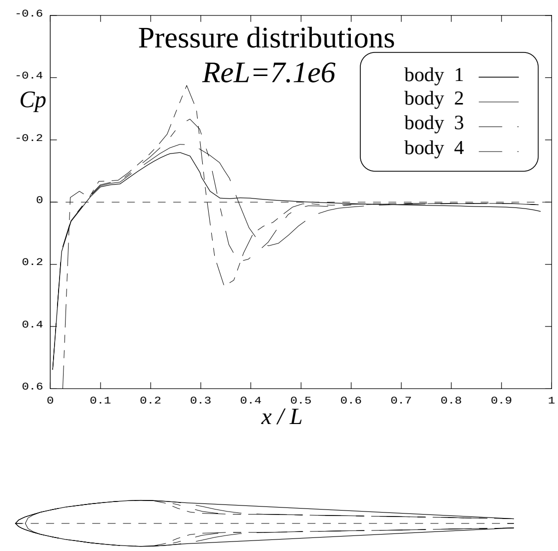

Fig. 2 : Althaus axisymmetric bodies

Table 1 : Althaus bodies exp./numerical drag coefficients and transition locations

The influence of fuselage contraction on fuselage drag for a real saiplane fuselage has been studied.

In fig. 3 both the shape of the original fuselage and the one with an increased contraction, together with the relative pressure distributions at an angle of attack alpha=1.8°, along the fuselage upper midline, are shown. A similar effect has been observed for the pressure distribution along lower midline. Viscous calculations have been performed for the two shapes at a Reynolds number of *ReL*=18e6, typical of sailplane fuselages in the high speed condition. Fig. 4 show the relative skin friction coefficient distributions. Contraction has been increased in such a way that transition location has been kept at the same position of the original fuselage shape both along upper and lower fuselage surface. Fuselage upper surface transition location in this flow condition has been estimated at *x/L*=0.32 (see fig. 3).

It is possible to notice that the increased contraction lead to a steeper adverse pressure gradient behind the pressure peak and to an higher favourable pressure gradient approaching the tail (see fig. 3). This results in lower skin friction coefficient values just behind the cockpit and slightly higher values in the tail region (see fig. 4).

It is evident that a skin friction coefficient reduction just behind the cockpit (where the wetted area is quite high) has more influence than a small increase in the tail cone region (where the fuselage diameter and the wetted area are small).
The drag coefficients evaluated by the code (using both upper and lower midline viscous analysis) for the original and modified shape are shown in table 2. The sensible skin friction coefficient reduction behind the cockpit, together with a wetted area reduction, lead to a fuselage drag coefficient which is about 12% lower than that relative to the original fuselage.
It is now clear that fuselage contraction can be an efficient way to reduce fuselage drag.
Fuselage contraction has to be limited because in low speed flight conditions (low Reynolds numbers) the steep adverse pressure gradient behind the cockpit could lead to flow separation or detrimental laminar separation. It is also evident that fuselage contraction is limited to a certain value by structural reasons or by the need to leave space for internal arrangements (retractable propeller for motorgliders).

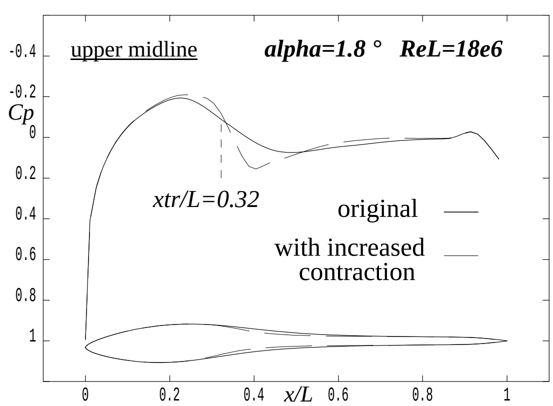

Fig. 3 : Effect of fuselage contraction on pressure distribution

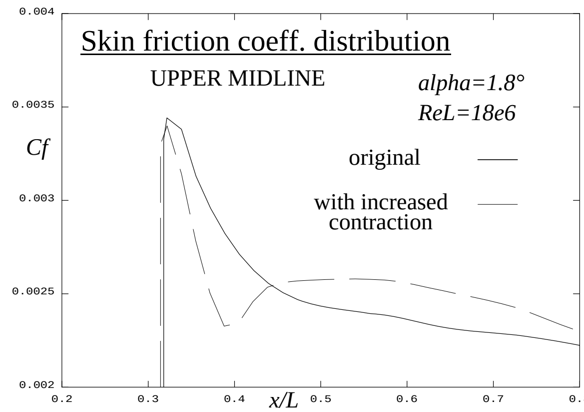

Fig. 4 : Skin friction coefficients distributions for original and modified shape

	Original	Incr. Contr.
CD	0.0349	0.0308 (-12%)

Table 2 : Influence of contraction on fuselage drag coeff. (based on max frontal area)

Effect of a cockpit lenght increase

The effect of a cockpit lenght increase (which could be important in view of crashworthiness measures) on fuselge drag has been investigated.
The lenght of the sailplane fuselage showed before has been increased "stretching" the cockpit of 20 cm (about 3% of the total lenght which is *L*=7 m). Fig. 5 shows the original and modified shape , together with the relative pressure distributions at alpha=1.8° along the fuselage upper midline. Viscous calculations have been performed again at *ReL*=18e6. The skin friction coefficient distributions along fuselage upper midline for the original and stretched fuselage are shown in fig. 6. A similar effect has been observed for lower midline.
The stretched shape is characterized by a less steep favourable pressure gradient in the forebody than the original shape (see fig. 5). This will lead to a lower skin friction in the forebody (fig. 6). In addition the wetted area added with the stretching is not so high, due to the lower radius at the fuselage nose. The stretched fuselage presents almost the same drag coeffcient than the original one (see values in fig. 6).
It is then of relevant importance to point out that on a sailplane, a cockpit lenght increase of 20÷30 cm (which would be very important

for pilot comfort and structural crash requirements) does not lead to any sensible drag penalty.

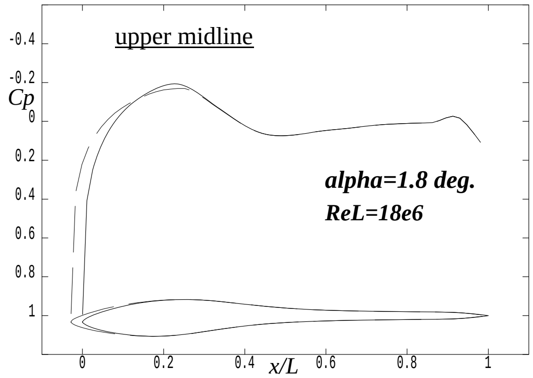

Fig. 5 : Effect of a fuselage "stretch" on pressure distribution

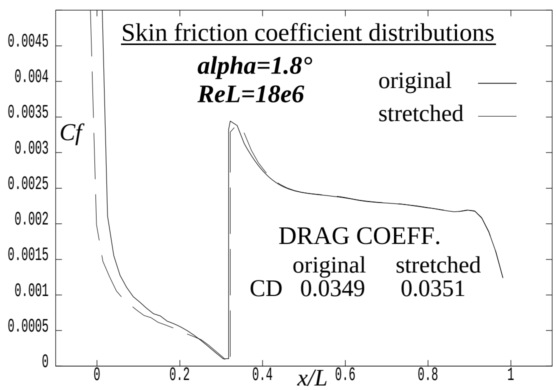

Fig. 6 : Effect of a fuselage "stretch" on *Cf* and drag coeff.

Effect of a cockpit height increase

For the same saiplane fuselage the height has been increased of about 10%. The original and modified shape, together with the relative pressure distributions (again along fuselage upper midline) are presented in fig. 7. The transition location is not influenced by the increase in height, but the increase in wetted area lead to a 14% higher drag coefficient.

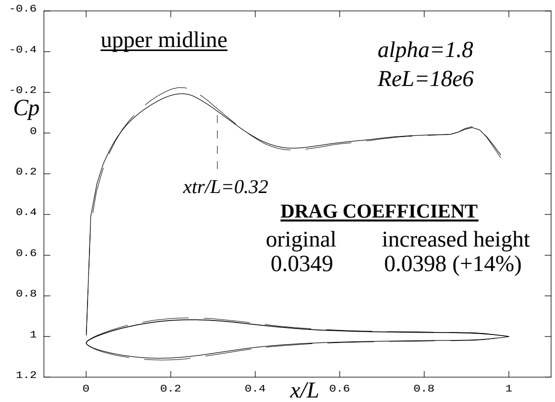

Fig. 7 : Effect of increasing fuselage height

Wing influence on fuselage aerodynamics

For general wing arrangements adopted in sailplanes (mid-high relative wing-fuselage position) the wing presence influences especially the pressure distribution on the upper part of the fuselage. In fig. 8 the pressure distributions on the sailplane fuselage with and without wing is shown. The presence of the wing causes an additional low pressure peak on the fuselage upper part, due to the strong induced supervelocities caused by the wing upper surface.

This low pressure peak influences transition location on fuselage upper surface and consequently the fuselage drag. It is then clear that the wing-fuselage relative wing position should be chosen in such a way to improve flow conditions on fuselage upper part, reducing fuselage drag.

It is also clear that the wing position has to satisfy additional constraints deriving from structural problems or sailplane longitudinal stability.

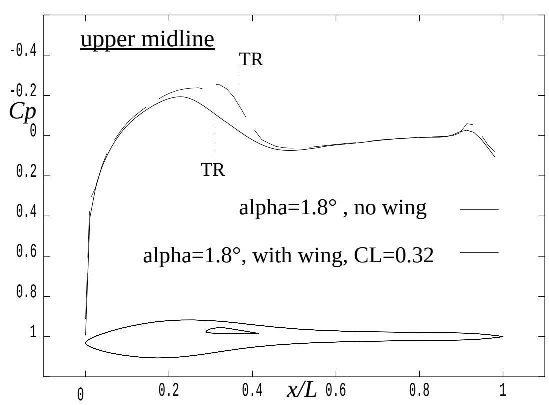

Fig. 8 : Wing influence on fuselage pressure distribution and transition location

Wing-fuselage junction design

The interference effects which are present on a high-performance saiplane wing-fuselage combination can be distinguished in non-viscous and viscous effects.

Non-viscous effects

Due to the displacement effect of the fuselage the streamwise pressure distribution on the wing changes towards the junction, depending on the relative dimensions and positions of the fuselage and wing and resulting curvature of the intersection lines. The shape of the fuselage contraction, in particular the width contraction, will affect the pressures on the wing root area.

Due to the circulation the flow in front of and behind the wing is curved. To minimize drag, the fuselage shape of a high-performance saiplane is fitted to the streamlines of the wing at a certain lift coefficient (usually for the best glide ratio).

At higher angles of attack there will be a crossflow and hence an upwash along the sides of the fuselage in front of the wing, named alpha-flow, which increases the angle of attack towards the wing root, see fig. 9.

At lower angles of attack there will be a downwash along the sides of the fuselage which decreases the angle of attack towards the wing root.

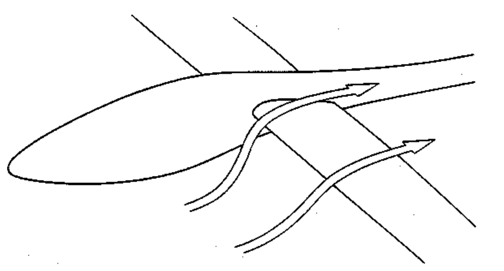

Fig. 9: Alpha-flow effects

Viscous effects

The boundary layer on the fuselage turns turbulent before the wing-fuselage junction, see fig. 10.

The turbulent boundary layer is not able to overcome the steep adverse pressure gradient in front of the wing-root leading edge and separates from the surface along a separation line along the junction. The separated flow rolls up into a vortex system wrapped around the wing root, and on the wing root a turbulent wedge originates at the leading edge.

At the higher angles of attack, due to alpha-flow, the position of transition on the upper surface of the laminar wing shifts forward towards the wing root and turbulent separation will occur at the rear of the root region if laminar flow airfoils are employed up to the fuselage.

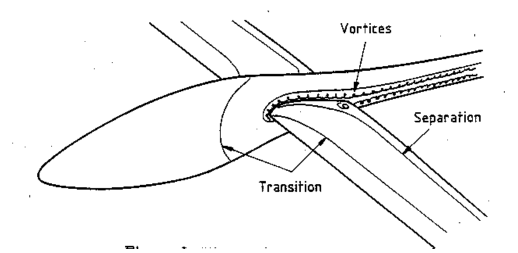

Fig. 10: Viscous interference effects

Design objects and tools

A wing-fuselage junction has been designed for an high-performance sailplane. The interference effects previously described were encountered by changing the laminar flow airfoil toward the fuselage in order to preserve the laminar flow pressure distribution as far as possible up to the turbulent corner flow, where the target pressure distribution is suitable for the turbulent flow conditions.

The wing-fuselage combination has been designed with the three-dimensional panel method KK-AERO, [ref. 5].

The code has a design option, where differences between design and actual pressure distributions are minimized iteratively using a numerical optimization technique and taking geometrical constraints into account.

Wing-fuselage junction design of an high performance sailplane

In fig. 11 the initial wing-fuselage combination is shown. The wing with nearly elliptical chord distribution employs the airfoil DU89-134/14 [ref. 1] in the inner part. This airfoil has a thickness of 13.4% chord and a camber changing flap of 14% chord.
Fig. 12 shows the airfoil shape together with the operational conditions relevant for the wing-fuselage combination design. Indicated with (1), (2) and (3) are the high-, medium- and low-speed conditions respectively.
It is well known that a laminar airfoil is not working really well in presence of turbulent flow conditions. It is easy to show [ref. 11] that such a laminar flow airfoil, at a lift coefficient Cl=1.00 (typical of the medium speed condition, or best glide ratio condition) in turbulent flow conditions presents an amount of separated flow at the trailing edge, while with a "turbulent" flow airfoil is possible to have completely attached flow on the upper surface at the same lift coefficient.
The pressure distribution typical of such a "turbulent" airfoil will be then considered as target for the pressure distribution on the wing at the junction.

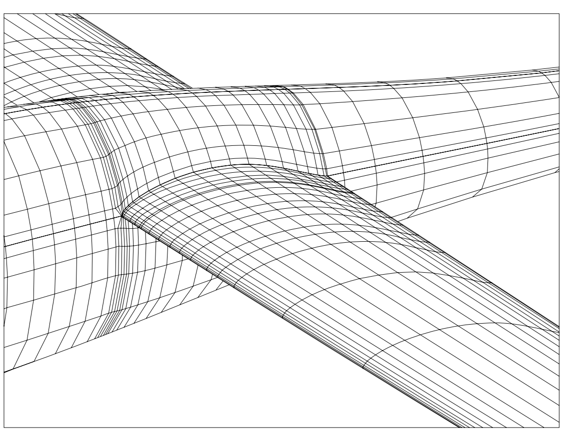

Fig. 11: Initial wing-fuselage combination

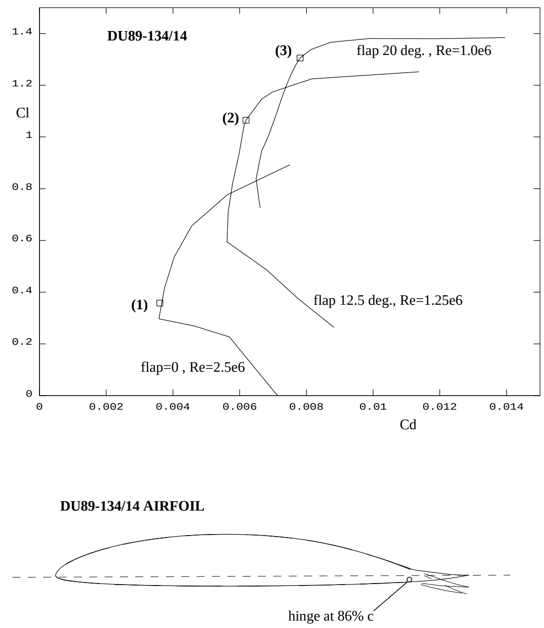

Fig. 12 : DU89-134/14 airfoil and operational flight conditions

In fig. 13 pressure distributions at the medium speed flight condition on the wing-root area of the initial wing-fuselage combination show suction peaks on the leading edge due to displacement and alpha-flow effects. In the same figure the target "turbulent" pressure distribution in the oblique section is shown.
During the design iterations using KK-AERO code, while attempting to realize the target pressure distribution in the region between the fuselage and the flap, it turned out that the new wing upper surface near the fuselage at 60% chord would be thinner than the initial shape. This undesirable sag in the wing-root region was eliminated by simply extending the chord at the wing root, thus creating a trailing edge fairing.
It also came out, during the iterative design procedure, that the target pressure distribution at the wing root, especially at the leading edge, would lead to an unrealistic shape. The target of the design was then changed , trying to obtain a pressure distribution with the same adverse pressure gradient but characterized by a higher level.
The design process finally lead to a new shape for the airfoil in the wing-root region. Particular care was taken in trying to have a smooth and nice-looking shape both along

the wing span and along the chord in each spanwise section.
In fig. 14 the resulting shape and relative pressure distributions in the medium speed condition are shown. It is possible to notice that the target pressure distribution (the same gradient) has been achieved in the oblique section close to the junction and that the target laminar flow pressure distribution has been preserved in the region where the influence of the prevoiusly described turbulent wedge disappears.
Fig. 15 shows the wing cross sections in the region between the root and the flap: the shape is blown up for the sake of clarity. This figure also show the changes on the lower surface, designed with the flap at the high-speed zero-degree deflection. It is possible to see that the wing thickness at the root has been increased, being this favourable also for structural reasons.
In fig. 16 calculated flow conditions on the wing upper surface at the medium speed condition for initial and final designed junction are shown.
It is possible to see that on the designed junction the flow separation at the junction has been removed and an improvement in sailplane performance is expected.

Conclusions

An investigation on fuselage aerodynamics has been done. A three-dimensional panel code has been used to solve the potential flow and viscous calculations have been performed along some streamlines on the fuselage leading to an approximate value of the drag coefficients.
The influence of fuselage contraction, of a cockpit lenght increase and of an increase of fuselage height on fuselage drag have been investigated.
It has been shown that fuselage contraction can be an efficient way to reduce fuselage drag, but it is limited to a certain value by aerodynamic, and structural reasons.
It has been shown that a cockpit lenght increase of 20÷30 cm does not lead to any drag increase.
In the second part of the paper, an analysis of the wing-fuselage interference effects has been done.
The design of an improved wing-fuselage junction for a high-performance sailplane has been presented.
Changing the airfoil in the wing root region, flow conditions at the junction have been improved. For the final design, the upper surface in the medium speed condition does not show any remarquable separation at the junction.
Although the benefits in performance could not be proven by windtunnel tests or flight tests yet, prototype of model with the new wing-fuselage junction is being produced in Germany.