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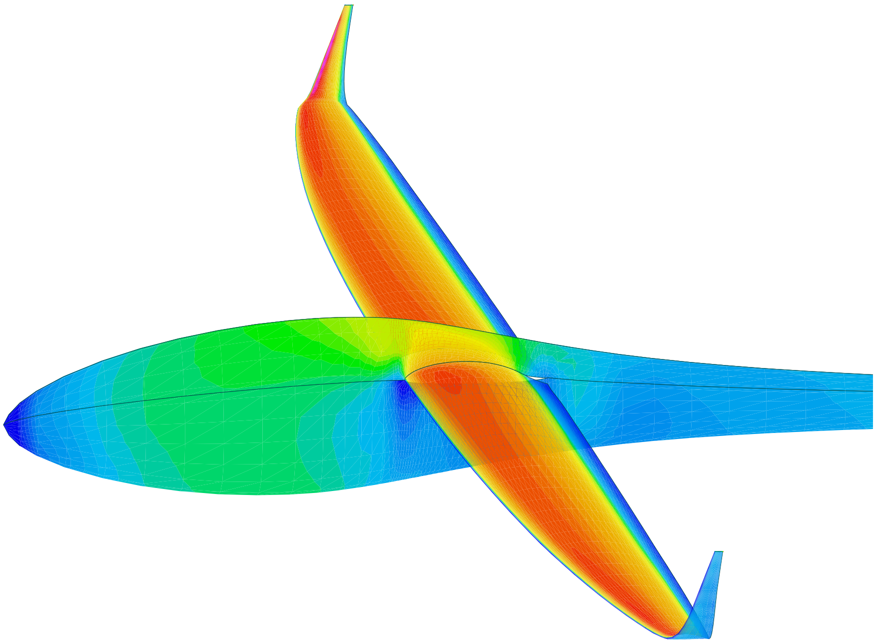

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Wing-Winglet Design Methodology for Low Speed Applications

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Winglets have recently became popular for high-performance sailplanes. Unlike airliners some different problems, such as: efficiency over the entire speed range (low to high wing CL) and low Reynolds number phenomena are of primary importance. Additionally the winglet should not cause excessive profile drag or deterioration of the directional stability, control and stall characteristics. Additional problems can occur when applying cruise flaps, which modify a load distribution at various flight conditions. This paper describes a wing-winglet design methodology based on Munk's theorem and multipoint numerical optimization. It was developed especially for high performance sailplanes, but could be easily applied to other subsonic aircraft. The methodology consists of two major steps. The first is the optimization of planform and two-dimensional airfoils, which fulfill requirements (in the two-dimensional case) for selected wing stations. After integration of the designed (optimum) sections into the three-dimensional configuration, certain adverse interference effects occur. In the second step, the multi-point inverse design/optimization method is used, which allows the determination of the geometry (sections shape, wing twist, angles of attack, flaps/controls deflections) which brings pressure distributions closest to the specified ones at some angles of attack (or at specified lift coefficients), minimizes induced drag at specified lift and moment coefficients (trim conditions), and enforces some geometrical constraints including a smooth geometry.

Introduction

WINGLETS, proposed by Dr. Richard Whitcomb at NASA Langley in the mid-1970's[1] for reducing induced drag, have been in common use, mainly for airliners, since late 70-ties. They allow for the reduction of induced drag by a few percent with only minor increase of wing bending moment and weight. The most common method for aerodynamic analysis and design of such devices is based on Munk's induced drag analysis in the Trefftz plane.[2,3] Winglets for low-speed aircraft have not been so popular. Recently they have been applied for high-performance sailplanes, mainly because of wing span limitation, higher ailerons efficiency, better overall flying qualities, and as an easy and low price means for maximum L/D gain. Unlike airliners, weight and bending moment are of secondary importance and the winglet design problem becomes one of pure aerodynamic performance. Instead some new problems, such as: efficiency over the entire speed range (low to high wing CL), strong aerodynamic interference at concave wing-winglet corner, and low Reynolds number phenomena are of primary importance. Additionally, winglets should not cause excessive skin-friction drag at high speeds, deteriorate of the directional stability (important because of very large span), control and stall characteristics. The additional problems can occur when applying performance flaps, which modify the spanwise load distribution at various flight conditions.

The most straightforward way to design the configuration with winglets is using a multipoint numerical optimization with proper objective functions. The limited accuracy of the existing computational methods in predicting final aerodynamic characteristics (especially for three-dimensional low Reynolds number flow) and very high computational cost are the problems in applying such the method.

There are few examples in the literature of the methodologies, more or less successfully applied for designing the winglets for sailplanes.[4–7] Most of them do not consider the detailed interference effects and are based on the two-dimensional airfoils characteristics. The easiest way for analyzing the influence of winglets on sailplane performance can be done by increasing the total drag due to the additional winglet profile drag and lowering the induced drag due to a winglet action. Such an analysis for a typical sailplane shows that winglets decrease induced drag by 5% and allow for about 3% lower sink velocity at low speeds and about 0.5-0.6% higher at high speeds. Some experiments and experience with winglets have shown that the benefits at low speeds could be even higher, but loses at higher speeds can be excessive. It is evident, that such analysis disregards some important phenomena. In addition, it is clear, that the potential

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flow methods, applied widely in aerodynamic analysis and design, also do not provide the complete image of phenomena having influence on winglets performance. This refers also to the Munk theorem applied to planar and non-planar configurations with regard to the conditions for minimum drag due to lift.

Understanding the phenomena having the most important influence on winglet effectiveness is the key issue for efficient wing and winglet aerodynamic design methodologies, as well for the selection of tools to use for the process.

Winglet and Wing-Tip Flow Considerations

Nearly all publications concerning the wing and wing-winglet performance analysis, consider the profile drag and induced drag as important for determining the overall aerodynamic efficiency. The total drag of the wing and winglet can be expressed as:

$$C_D(C_L) = C_{D_{wing\_prof}}(C_L) + \frac{\Delta S_{winglet}}{S_{wing}} C_{D_{winglet\_prof}}(C_L) + \frac{C_L^2}{\pi \Lambda} K_V$$

The second term is the additional drag due to winglet profile drag (also dependent on lift). K_V is the vortex drag efficiency factor due to the winglets.

As pointed out above, such analysis is not sufficiently accurate for design purposes. In many cases it can even lead to wrong qualitative conclusions. The reasons are the adverse aerodynamic interference effects and the complicated, nonlinear nature of the flow field at the wing tip. The issues cannot be solved directly using potential methods.

Some practical observations, flight experience, and common opinion of sailplane pilots state that wing planform, taper ratio (or rather tip chord) and winglets have much higher influence on the low speed characteristics than would be expected based on classical theory of a wing of finite span. Especially interesting observations and conclusions are:[8] "winglets can produce a dramatic improvement" in low-speed characteristics and "the height of winglets did not seem very important". Such conclusions seem general and, as a result, winglets are currently applied even on sailplanes with very high aspect ratio (e.g. new German sailplane *Eta*, having aspect ratio 51.3).

An interesting computational and experimental results for the wings with various nonplanar shapes of the wing tip are these of Naik and Ostowari.[9] Applying a nonlinear panel method (with wake relaxation) for such configurations[6,9] the conclusion is that a wing tip pointed down is less efficient than one pointing up. Experimental results show exactly the opposite - and the differences are significant. There are few phenomena, apart a well known effect of vortex drag reduction due to nonplanar wake, which have influence on final efficiency of nonplanar configuration and could explain such results. The most important is aerodynamic interference. In the Fig. 1 the isobar pattern is shown in the concave corner between wing and upper winglet. A region with high velocity and negative pressure, as well high pressure gradients downstream are observed and lead to drag increment or even to flow separation. There are no such effects in the case of drooping wing tip. In any case, the viscous drag is different than it is for the case of two-dimensional airfoil flow.

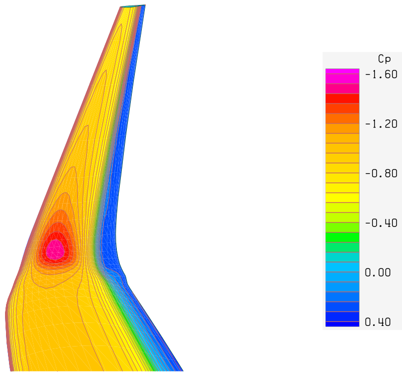

Fig. 1 Pressure distribution in the wing-winglet concave corner.

As early as the mid-70's Whitcomb[1] considered in detail influence of aerodynamic interference on the final aerodynamic efficiency of winglets. These considerations led to a layout with two winglets: a forward one in the region with high local velocity on the upper surface pointed down (to prevent superposition of high negative pressure fields of a wing and winglet) and rear one in the region with limited negative pressure, pointed up. Such the interference problems are especially important in transonic and low Reynolds number flows.

The next effect, which can influence winglet efficiency, is boundary-layer cross-flow. It is rather obvious that a wing equipped with winglet should experience such an effect, but weaker than a planar wing.

Another important effect influencing a drag, which should be considered, is a nonlinear lift (load) at wing tip due to a vortex separation at the side edge.[10] It can lead to higher local load at a wing tip (vortex lift), but the additional pressure force acts in direction perpendicular to wing surface (no corresponding leading-edge suction force) increasing the drag due to lift. These conclusions are in agreement with experimental results. It should be noted, that such a problem cannot be solved in a proper way using potential flow methods. Analysis based on potential flow leads to exactly opposite conclusion: that the drag is decreased.[3] A more detailed quantitative analysis of this effect could be done applying Polhamus suction analogy extended to the side (or tip) edges[11,12] - see Fig. 2, or using field methods (Euler or Navier-Stokes solution).

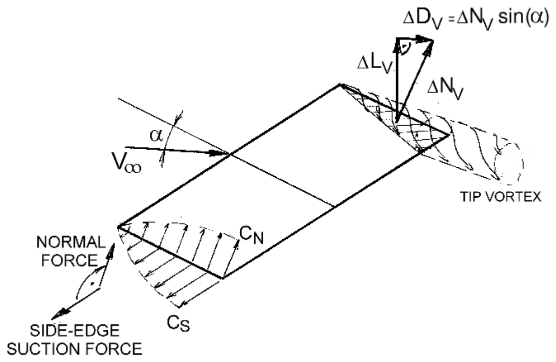

Fig. 2 Tip vortex action and suction analogy.

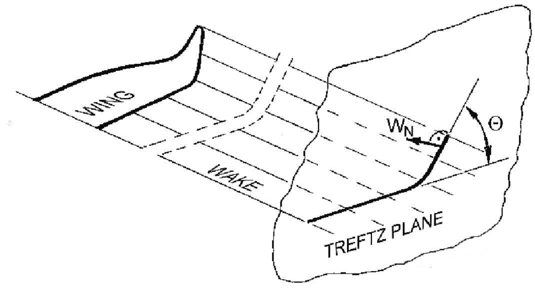

Fig. 3 Trefftz plane analysis.

For the wings with winglets, these nonlinear effects could be very weak, because of short edge and small changes in winglet angle of attack relative to the free stream for the nearly vertical surface. These conclusions suggest that winglets can offer additional benefits compared to a planar wing and, more important, that potential flow methods are better suited for the analysis of wing-winglet configurations than for planar wings.

The above conclusions lead to a modification of the expression for winglet efficiency:

$$C_D(C_L) = C_{D_{wing\_prof}}(C_L) + \frac{\Delta S_{winglet}}{S_{wing}} C_{D_{winglet\_prof}}$$
$$+C_{D_{interf}} + \frac{C_L^2}{\pi\Lambda} K_V + \Delta C_{N_{VORTEX}} \sin\alpha_{wl}$$

From the above expression the features of the proper design methodology for wing-winglet (or even wing-winglet-tail-fuselage) combination can be designated. At a given amount of induced drag reduction (relative elliptic load distribution on a planar wing) it suggests that the wing profile drag as well as the winglet wetted surface and profile drag should be minimized, and the adverse aerodynamic interference should be eliminated. The last term in the above expression, which corresponds to vortex separation at the wing tip (see 2), is assumed to be negligible in the case of a well-designed winglet with vertical end panels - leading to benefits compared to a flat wing greater than might be expected.

Wing Layout Specification

The optimum load distribution which leads to minimum induced drag of nonplanar configuration can be easily found applying Munk's theorem. Assuming a straight wake parallel to undisturbed velocity, the required condition for minimum induced drag is that the velocity component normal to a wake in the Trefftz plane must be proportional to cosine of the local dihedral angle (see Fig. 3): $w_n \sim \cos(\Theta)$. It depends on lifting surface layout in x-z plane, especially on the winglet height, its dihedral and radius of the wing-winglet junction.

An optimum wing planform at the initial design stage can be easily found, assuming that sectional lift coefficient is close to airfoil optimum (depending e.g. on local Reynolds Number). A local chord value along the span can be expressed as:

$$c(s) \sim l^{OPT}(s)/c_l^{OPT}(s)$$

where l^{OPT} and c_l^{OPT} are optimum sectional load and optimum sectional lift coefficient respectively. For specified wing lift coefficient C_L (different from the airfoil optimum), and constant airfoil characteristics along a span (so, neglecting Reynolds number effect) and typical convex airfoil drag characteristics (see Fig. 4) it is easy to show that the optimum sectional lift coefficient is constant along a span. In the case of nonuniform lift coefficient distribution the lower value of c_l at one section must be compensated by higher value at the second one, in order to maintain fixed wing C_L. Drag increment at the second section is always higher than decrement at the first one, leading finally to some extra wing profile drag - Fig. 4.

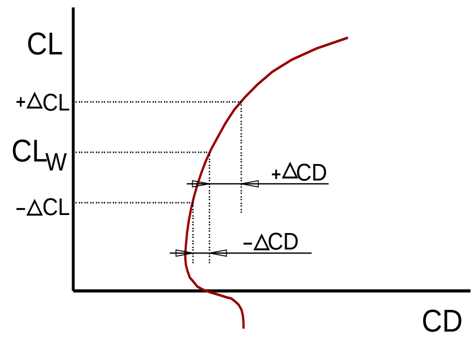

Fig. 4 Profile drag increments due to lift variations

For such a planform and load distribution, both induced drag and wing profile drag reach their minimum values. For a case of multi-point design (low to high speeds - high to low wing C_L) optimum sectional lift coefficient is almost constant, nearly independent of airfoil characteristics.

The vertical winglet surface has no contribution to the wing total lift, and a lift coefficient on a winglet should correspond to max. profile L/D. In this case the required amount of winglet lift (for minimizing wing induced drag) is produced at minimum of winglet profile drag. For multipoint design it must be determined after detailed design at next design stages.

A final wetted area of a wing-winglet combination with a planform (chord distribution), initially specified as above, depends on lifting surface layout in the y-z plane. It is easy to check that the tip of the winglet panel should be vertical for a limited total span. The other important parameter is radius of the wing-winglet junction. Fig. 5 presents the required total winglet height for 15m wing span at various amount of induced drag reduction and radius of wing-winglet junction.

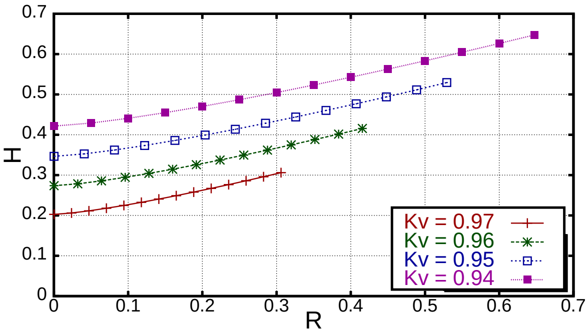

Fig. 5 Required total winglet height for specified amount of drag reduction and junction radius.

Fig. 6 presents the influence of that radius on the total area increment (for a constant sectional lift coefficient) for 5% induced drag reduction, relative optimum of a planar wing.

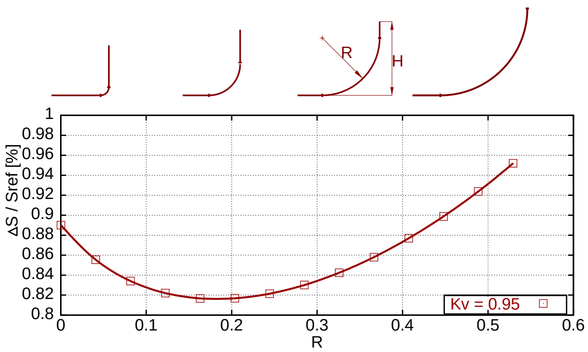

Fig. 6 Relative increment of the area of wing-winglet combination for 5% induced drag reduction

It is seen, that there is an optimum of the layout, leading to the minimum wetted surface increment. An even slightly lower increment could be obtained using a more complicated, entirely nonlinear shape. It is an important conclusion that the sharp wing-winglet junction is inappropriate because of two reasons: larger required additional wetted surface for specified amount of induced drag reduction, and strong adverse interference in the sharp corner.

A planform obtained by above procedure is the initial one. A number of adjustments must be made in order to obtain the proper range of lift distributions, stall characteristics, and directional stability.

The wing-winglet airfoils should have the proper aerodynamic characteristics over the entire range of flight conditions: angles of attack, cruise flap deflections and through some range of side-slip angles. It is possible computationally to find increments of the lift coefficient at various span stations due to angle of attack changes, cruise flap deflection and side-slip flight conditions. The Fig. 7 shows the c_l distribution for various total wing lift. The s coordinate is the arc length coordinate along the wing (after surface development). It is seen, that range of c_l changes on winglet is narrower compared to the wing sections (and additionally can be slightly controlled by winglet sweep). This effect is especially strong when using cruise flaps and a rather small radius of the wing-winglet junction. It usually allows for specifying higher design value of a winglet section lift coefficient, and additional modification of a winglet planform, lowering local chords and final wetted surface. This modification must be done together with airfoils designed in an iterative manner.

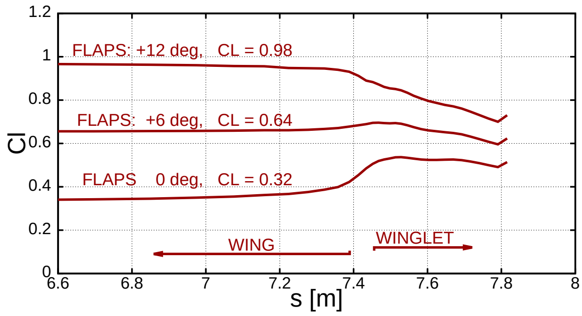

Fig. 7 Spanwise lift coefficient distribution for various wing lift and flap deflections

A sample planform is presented in Fig. 8 for both: a constant c_l and for that finally specified.

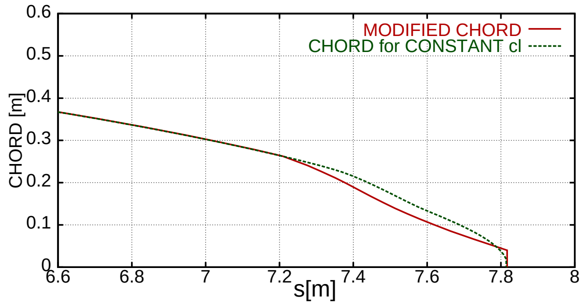

Fig. 8 Wing-winglet chord distribution: optimum for constant sectional c_l, and after modification

Finally, for the designed planform, we can determine the dependence of local sectional lift coefficient along a span on wing total C_L. It gives us the design range of lift coefficient and, for given value of the wing load, Reynolds number at which an airfoil in each wing section operates.

Airfoils Selection and Design

The knowledge of the sectional lift coefficients and Reynolds numbers allows for the proper design of the two-dimensional airfoils, which leads to a maximum efficiency of the final wing project. Because of rather advanced level of development of computational methods for viscous flow over airfoils, it is currently the procedure that airfoils are design specifically for various stations along the span.[13] This allows for the optimum use of airfoils for a specified wing. Currently, probably the most efficient methods for such a problem solution are inverse design and optimization technique. Optimization alone sometimes leads to artificial results. Probably a mixed method is the most promising: optimization for obtaining the required design directions and the final design using an inverse method. During the present investigation such a treatment has been applied. The initial stage was an multipoint airfoil optimization using the MSES/LINDOP programs,[14] and the XFOIL program[15] was used for final inverse design and analysis of two-dimensional aerodynamic characteristics. In the case of airfoils for winglets, beside the requirement of drag minimization in the above specified range of lift coefficients, the drag characteristics should not distort the directional stability. The problem is generally of secondary importance, since yawing moments due to nonsymmetrical drag on winglets at side slip conditions are usually much lower than those due to side force on the vertical tail. Because of large wing span of high-performance sailplanes, it could be generally desirable that a leeward winglet experiences no more drag than does the windward one, especially at extreme conditions.

Fig. 9 presents the spanwise lift coefficient distribution on the sample wing and winglet at a wing $C_L = 0.24$ and angles of side-slip of 0 and +/- 3 deg. Similar distributions can be calculated for other wing lift values. Computational characteristics of one of airfoils designed for winglet are presented in Fig. 10. Signs indicate design values of sectional lift coefficient at different speeds. The curve limits correspond to +/- 3 degrees of side-slip angle.

The calculations were performed using critical amplification ratio $n = 12$ for analyzing boundary layer transition. The typical value $n = 9$ leads to weaker laminar separation bubbles and better computational characteristics at each of the design points. Free transition was assumed, and with no turbulators on the airfoil. There are three reasons for such an assumption:

- difficulty in employing a turbulator on the upper winglet surface due to relocation of laminar separation bubbles with changes of angle of attack and Reynolds number,

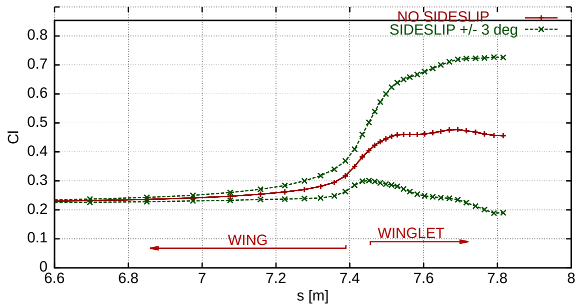

Fig. 9 Lift coefficient distribution at wing $C_L = 0.24$ and various angles of side-slip

- the drag of the turbulator itself could be excessive,

- an expected lower additional drag caused by laminar separation bubble on the airfoil mounted on the vertical winglet compared with the two-dimensional characteristics.

The last conclusion is based on the observation that the slope of the winglet surface with a separation bubble (and additional negative pressure) related to undisturbed velocity is smaller than for two-dimensional airfoil flow.[16]

It should be pointed out, that for a typical sailplane winglet at low Reynolds numbers, one of the critical airfoil parameters is the relative thickness. In this case slightly over 10% was specified as a geometrical constraint.

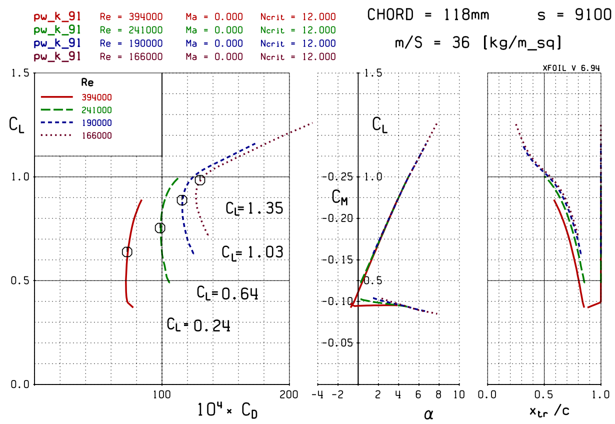

Fig. 10 Calculated aerodynamic characteristics of airfoil designed for winglet section.

Three-Dimensional Design - Aerodynamic Interference

After assembling wing section designs and the optimum planform into a three-dimensional configuration, some adverse interference effects occur, observed in the Figure 1. This modifies pressure distribution, boundary layer development and skin friction, a load and circulation distribution, and induced drag finally.

In order to avoid these adverse interference effects, an inverse design/optimization method[17] can be used. It allows one to find the external shape of the three-dimensional configuration that produces the pressure distributions closest to the target at a few design points (design angles of attack) and configurations (flaps/controls deflections). Additionally, induced drag can be minimized at specified lift and longitudinal moment (trim conditions), and some additional geometrical constraints can be enforced. The following objective function is minimized:

$$E = \sum_{n=1}^{N_{DP}} W_{P_n} \cdot E_{P_n} + W_C \cdot E_C + W_R \cdot E_R + \\ + \sum_{n=1}^{NDP} W_{D_n} \cdot (C_D)_n + \\ + \sum_{n=1}^{N_{DP}} \lambda_n^L \cdot (C_L - C_L^D)_n + \sum_{n=1}^{N_{DP}} \lambda_n^M \cdot (C_M - C_M^D)_n$$

where n is design point number, N_{DP} is the number of design points, W_P, W_C, W_R, W_D are weight factors for pressure deviation norm, geometry constraints penalty function, regularity term, and induced drag respectively. E_{P_n}, E_C, E_R are: pressure distribution deviation norm (target - actual) at $n'th$ design point, geometry constraints penalty function, and regularity term. $(C_L^D)_n$ and $(C_M^D)_n$ are design lift and moment coefficients at $n'th$ design point.

A flow analysis is performed by a higher-order panel method, and the design problem is solved by numerical optimization. A very inexpensive and efficient method of sensitivity analysis is performed by applying a transpiration technique. An induced drag analysis is performed in the Trefftz plane.

As a result, it is possible to determine the geometry (surface shape, wing twist, angles of attack, flaps/controls deflections) which produce pressure distributions closest to those specified at some angles of attack (or specified lift coefficients) and configurations, which minimize the induced drag at specified lift and moment coefficients (trim conditions) and enforces some geometrical constraints and regular (smooth) geometry. The package is very useful for the aerodynamic design of complex configurations at low speeds, and was applied in designing most of high performance German sailplanes (ASW-27, Ventus-2, Antares, ASW-28) in order to remove both, inviscid and viscous adverse interference effects.[13,18] This allows for significant improvement of final performance.

In Fig. 11, one can see the geometry after design iteration enforcing specified (quite artificial) constant pressure along the winglet span. The wing-winglet layout is the same as in Fig. 1. It is seen, that it is possible to remove the pressure peak by changing the sectional geometry and twist distribution.

A similar calculation can be performed for actual design. The target design pressure distributions on

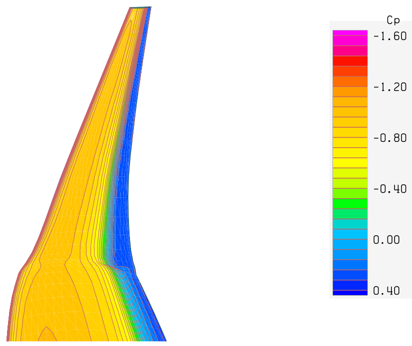

Fig. 11 Pressure distribution in the wing-winglet region after 3D inverse design iteration.

the critical parts of the surface at various sailplane lift coefficients and flap positions are taken from the previous two-dimensional results. Sometimes it is better to modify the design pressures slightly by shifting the two-dimensional distribution towards higher negative pressure, but maintaining the pressure gradients.[18] Also the induced drag coefficient is minimized for the actual, three-dimensional geometry, taking into account aerodynamic interference. The optimum load distribution obtained from Munk's theory does not exactly correspond to the actual one on the three-dimensional configuration (but the circulation distribution does) because of higher local mean velocity in some wing/winglet sections caused by aerodynamic interference. Also influence of the fuselage on wing load distribution and the final induced drag, as well as influence of horizontal tail (trim drag), are taken into account in the presented method.

Sample Results

The computational methodology presented for wing and winglet design was developed for practical applications. An influence of some basic design parameters on the efficiency of the final configuration can be studied at the initial stages of a design procedure, for example, the influence of the lifting surface layout on the additional wetted surface. An influence of some geometrical and aerodynamic parameters on the final objectives is usually more complicated and can be checked only by performing an entire or part of the design procedure. Assuming that three-dimensional adverse interference effects will be removed at the final design stage, the influence of such parameters as radius of wing-winglet junction, winglet sweep, tip chord etc. on final efficiency (sectional airfoils characteristics are assumed to be known and the same as in two-dimensional case) can be analyzed.

Figure 12 presents the influence of wing-winglet junction radius on the induced drag reduction over the range of lift coefficients in case of fixed wing geometry and 15m span (corresponding to Standard Class sailplane). The winglet height for each case is

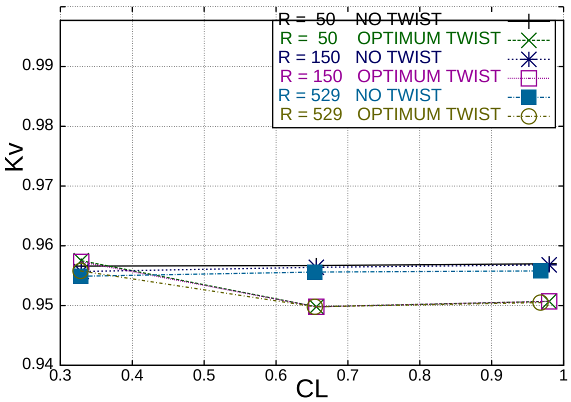

Fig. 12 Induced drag efficiency factor for fixed wing geometry.

specified in such a way, that at the optimum lift distribution it allows for a 5% induced drag reduction ($K_V = 0.95$). The local chords are proportional to the optimum load distribution. Two cases have been studied: a wing-winglet with no twist and one with optimum twist (and load distribution) obtained with multipoint design/optimization process. It is interesting, that all radius cases are nearly equivalent from a viewpoint of induced drag reduction. Wings without twist are slightly less efficient (about 0.6% higher induced drag than theoretical minimum at entire lift range) than the optimum ones. An optimization of geometry leads to nearly the theoretical minimum at higher lift coefficients with some (negligible) penalty at low C_L. Such results indicate, that designing of mentioned wing-winglet configuration is rather easy problem with respect to induced drag. Taking into account the skin-friction drag, the junction radius of about 150 – 200 mm seems to be optimum - minimizing the wetted surface (required surface for this winglet is about 20% lower than for $R = 529mm$ - fully circular tip). On the other hand, higher R values allow for minimizing the interference effects. In all cases proper winglet airfoils design/selection is important for success.

Figure 13 presents the influence of wing-winglet junction radius on the induced drag reduction of 15m span wing equipped with cruise flaps (corresponding to a Racing Class sailplane). The changes in wing lift coefficient in this case are obtained mainly by changing flap deflection, modifying the spanwise load distribution. A flap span was limited to the flat wing surface (up to the beginning of a curved wing-winglet junction).

In this case, the results are completely different than those for the unflapped glider. A rather small radius of junction is optimum. Higher values lead to poorer performance away from the design point. A proper design of such a configuration is much more demanding. A radius of about 100 mm seems to be reasonable, leading to small wetted-surface increment and good "off-design" characteristics. A careful airfoil design and removing the adverse aerodynamic interference are of primary importance. Unlike the previous case, the choice of large junction radius is completely unacceptable, leading to higher skin-friction and induced drag.

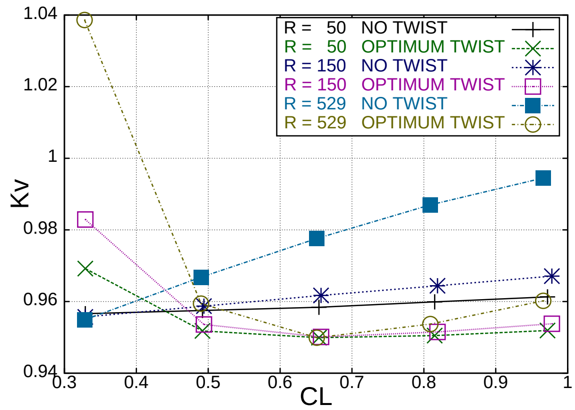

Fig. 13 Induced drag efficiency factor for wing with cruise flaps.

In the similar way it is possible to analyze influence of winglet sweep angle. Computationally it does not to be very important, but higher sweep allows for slightly better behavior at "off-design" conditions (leading to slightly wider range of acceptable lift coefficients) and lowers the negative pressure spike at wing-winglet junction. The last result can be obtained also by modifying the wing sections in the junction.

Some computational results suggest that higher values of winglet design lift coefficient (leading to smaller chords and higher positive twist) lead to slightly better "off-design" behavior and a better overall design.

The Fig. 14 presents a part of wing-winglet-fuselage-tail configuration with cruise flaps after three-point design performed during studies of high performance sailplane of 18 m span. The winglet height and planform allow theoretically for a 5% induced drag reduction.

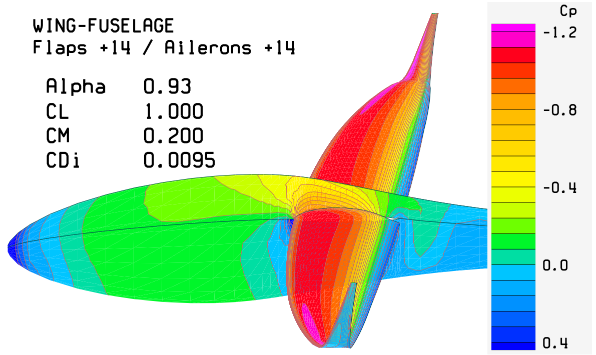

Fig. 14 Wing-winglet-fuselage after designing.

The final geometry was determined by the inverse design-optimization process. Design pressure distributions on the wing and winglet surfaces were taken from two-dimensional airfoils, designed by MSES and XFOIL programs, for the flow conditions specific for each span station and flight condition (ten airfoils for various wing and winglet stations were designed). The final sections on the wing and winglet differ from two-dimensional airfoils, but produce pressure distributions close to those designed for two-dimensional flow (though avoiding three-dimensional interference effects). The total increase of the wing wetted area due to the winglet in the example is only about 0.6%, and it allows a reduction of induced drag of about 5% over nearly the entire design lift range ($C_L = 0.24$ to 1.00) and above. The trim conditions at a center of gravity corresponding to a 20% static margin were specified (this value was found to be about optimum). The inevitable skin-friction drag increment due to additional wetted surface of the winglet at high speeds is expected to be lower than 0.5% of the total sailplane drag. This should be compensated by a reduction of drag due to lift even at low wing C_L's. As observed in Fig. 15, the twist of the winglet just outside the cruise flaps was quite complicated, with rapid changes of sectional geometry in this region.

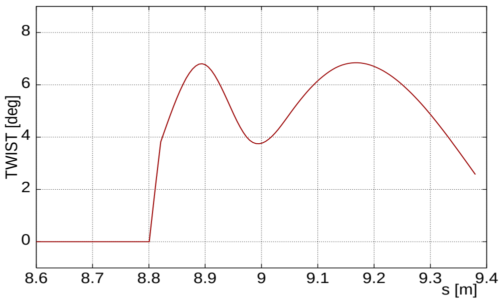

Fig. 15 Designed twist distribution near the wing tip

Concluding Remarks

The wing-winglet design methodology presented has risen as a part of a design study of high performance sailplanes. The design method is based on the concept of neutral interference. It was assumed, that the aerodynamic characteristics of configuration components (airfoils) are directly applied to the three-dimensional configuration, because all (adverse) aerodynamic interference effects are removed. In fact, some effects will not be canceled, e.g. cross-flow effects in the boundary layer - but they should be weak because of small spanwise pressure gradients after detailed design. A more attractive design idea is one having favorable interference (with better overall characteristics compared to the sum of component ones), but accuracy of existing analysis and design methods for three-dimensional flow at low Reynolds numbers is currently not sufficient to allow this. Most currently employed design methods for winglets are based on two-dimensional characteristics with no detailed corrections for three-dimensional integration of the configuration. The results of example designs show, that the methodology should lead to efficient final configuration with predictable aerodynamic characteristics. The method, like almost all design methods, is iterative. This is because some (both geometrical and aerodynamic) configuration parameters must be initially assumed and, after final design, must be modified. The design has not yet been verified experimentally, but the presented work is not completed. There are the plans for further investigations, both computational and experimental, as well flight-testing the final results. The methodology was developed for low-speed sailplanes, but almost without modifications can be applied for other low/middle speed aircraft.

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