The influence of target function selection on the optimization of winglets for the glider SB 15

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Abstract

The present paper is about an investigation into the influence of target function selection on the final results of an automated process for glider optimization. For this purpose the design parameters of a winglet for the glider SB 15 were exemplarily optimized by using different target functions, like minimum drag for a single target lift or a combination of target lifts. Results indicate that the influence of the target function for the used example is less significant than one might expect. Additionally the validation results for the process-chain that was developed are presented: not only proving the capability of the chain to predict drag deltas, but also indicating its limitations for the prediction of absolute drag values.

Introduction

In order to apply an optimization procedure to an aero design problem, one has first to develop a stable program chain to accurately evaluate all necessary aerodynamic characteristics of a complete sailplane configuration. When using such a chain within an optimization environment, one has also to define a feasible set of parameters with the respective boundaries and constraints as well as a target function for the given optimization task.

Whereas the parameters and the constraints are strongly dependent on the specific optimization task, the process chain and the target function are, within the scope of glider-optimization, more universally applicable. While it is obvious that the scope of a glider optimization is the increase of average cross-country speed, the calculation of the cross-country speed is dependent on the correct application of the weather-model which is a difficult task. Finally it is not necessarily intended to determine the exact cross-country speed, but to identify the parameters leading to the most beneficial geometry. Therefore it might be asked, if the selection of the target function has a significant influence on the geometric properties. The present paper tries to answer this question with the example of optimizing a new set of winglets for the glider SB 15 currently under construction at Akaflieg Braunschweig.

Process chain

An overview showing the principle of the applied process chain is sketched in Fig 1. The main components are the optimizer, a multi non-planar lifting-line method developed by Horstmann (program “Lifting-Line”, [1]) and the well known airfoil design an analysis program system “Xfoil” from Drela, [2].

With respect to this process chain, the total drag coefficient C_D of a sailplane configuration at a given total lift coefficient C_L can be split up into three components:

$$C_D = C_{Di} + C_{Dp} + C_{D,rest}$$

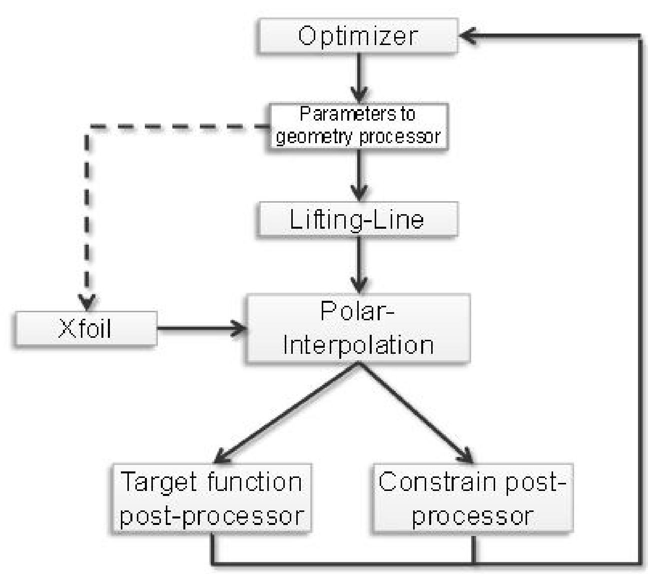

Fig. 1: Principle of the optimization process chain.

Presented at the XXXII OSTIV Congress, Leszno, Poland, 8 – 13 Jan. 2014

This article was peer reviewed by two independent, anonymous reviewers. The review process was overseen by Associate Editor Götz Bramesfeld

Here, C_{Di} is the induced drag coefficient which is provided by "Lifting-Line", while the second coefficient, C_{Dp}, is the profile drag of the complete wing. It is integrated from local profile drag coefficients c_{dp} along span. These, in turn, are computed with "Xfoil" based on local lift coefficients c_l according to the spanwise load distribution obtained from "Lifting-Line". A more detailed description of the procedure can be found in [3].

The last term $C_{D,rest}$ contains the drag created by fuselage, vertical and horizontal tailplane as well as interference effects. $C_{D,rest}$ can be estimated by comparing simulation results with flight performance measurements of similar glider types or, if not available, out of text books like [4].

The additional tools of the process chain satisfy pre- and postprocessing requirements, like e.g. the target function postprocessor to compute the average cross-country flight speed, based on the computed lift to drag polar and the applied weather model. While "Xfoil" and "Lifting-Line" are available free of charge, the used optimizer-environment "pyranha" is a DLR internal python-based optimization platform. "pyranha" contains different classes of optimization strategies like evolutionary algorithms or algorithms for gradient based optimization. In the context of the present study the "SUBPLEX" algorithm [5] is used for optimization. This algorithm can be regarded as a fair compromise between evolutionary algorithms which are very good in finding the global optimum but are very slow, and gradient based methods which are very fast but tend to find only local optimums. A disadvantage of said optimization algorithm is the fact that its performance decreases significantly when using more than approximately fifteen parameters.

The optimization problem

The design task selected to test the optimization procedure was to optimize a new set of winglets for the glider SB 15 of the Akaflieg Braunschweig. The 20m double seater class glider SB 15 is based on the 18m span SB 14 wings which are elongated in the inner part and already equipped with state of the art winglets [6]. The existing baseline provides a good reference for the optimization procedure. The current winglets can be detached from the wings to allow an easy exchange for any planned performance flight test. The optimization is therefore limited to the region outside the wing-winglet connection as shown in Fig. 2.

With respect to the parameterization of the winglet geometry, Fig. 3 provides an overview of the optimized quantities. Logically the span is fixed due to the 20m constraint and therefore was not changed. The winglet airfoil was not optimized and was chosen to be the same as the airfoil designed for the reference winglet by Scholz [6]. The most important parameters are consequently the winglet height h, the twist distribution, varying from ε_{Foot} to ε_{Tip}, and the winglet planform given by the local chord length varying from foot (l_{Foot}) to tip (l_{Tip}).

The cant angle ν_{Wi} was identified to be a parameter of minor importance, as in the present case the space between the wing-winglet connection of the existing wing and the span-limit

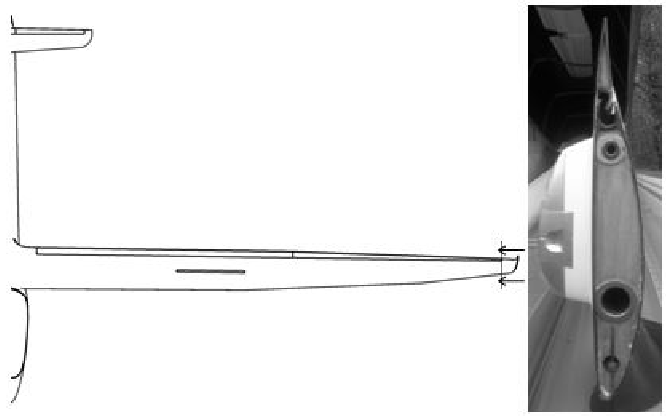

Fig. 2: SB 14 (and SB 15) wing-winglet connection.

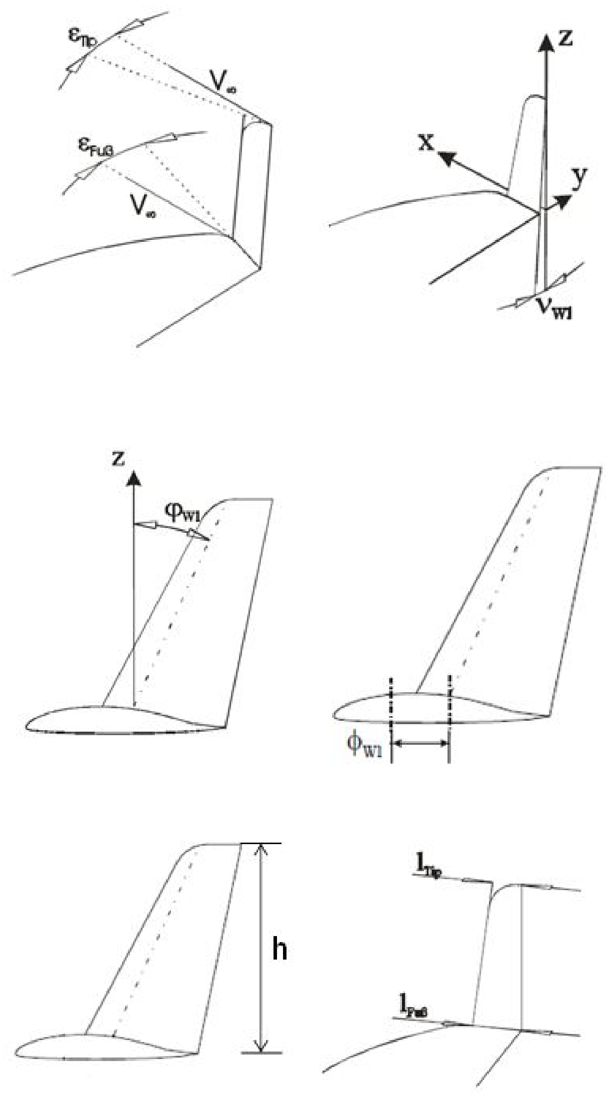

Fig. 3: Overview of optimization parameters.

of 20m leaves very little room for variation which is especially true for large winglets. Furthermore, a smoothly rounded wing-winglet junction instead of a sharp edge that might induce flow separation was also considered to be of importance. Therefore, the cant angle was set to a fixed value, leading to a nearly vertical planar-part of the winglet in flight.

Sweep angle φ_{Wi} and chordwise positioning ϕ_{Wi} of the winglet were also considered, but those parameters have only a minor influence on the optimization results using the discussed process-chain. This does not mean that those parameters are not important for the detailed design, but in order to demonstrate the influence of target functions onto the optimization result, their influence is of minor importance.

Target functions

As stated in the abstract, the main goal of the present work is the investigation into the influence of different target functions on the optimization results. For the context of this paper, three different types of target functions have been analyzed:

1. The simplest form of a target function is the minimization of drag for a constant lift coefficient. Within the scope of this work optimizations for three different lift-coefficients have been carried out:
   - $C_L = 1.3$ representing a low speed situation like circling in a thermal.
   - $C_L = 0.9$ leading to a result most beneficial in order to increase the maximum achievable glide ratio $(C_L/C_D)_{max}$
   - $C_L = 0.5$ aiming to minimize the impact of a winglet between strong thermals flying with relatively high speeds
2. In order to optimize the winglet to be beneficial over a broader range of airspeeds, the combined drag for more than one lift coefficient needs to be reduced. The selection of lift coefficients and the weighting between those can be expected to have a strong influence on the optimization result. In order to select those values properly a detailed analysis of logger data as it was done by Sherrer [7] would be beneficial. This paper includes optimization results for an equally weighted combination of glide ratio C_L/C_D at $C_{L,1} = 1.3$ and $C_{L,2} = 0.5$ leading to the subsequent objective function (with $\overline{X}$ being the set of free optimization parameters):

$$minf(\overline{X}) = \frac{C_{D,1}(C_{L,1},\overline{X})}{C_{L,1}} + \frac{C_{D,2}(C_{L,2},\overline{X})}{C_{L,2}}$$

3. The third class of target functions are those based on the computation and maximization of the average cross-country speed, based on a predefined weather model. In the context of the present paper the newly defined weather model is based on the one developed by Horstmann [8] with extensions from Ronig [9].

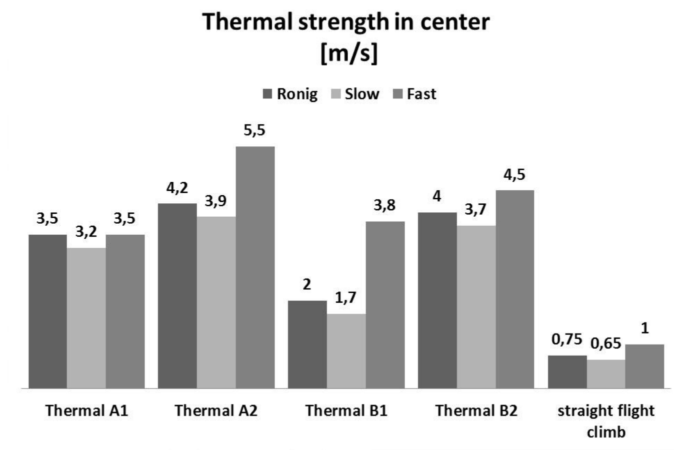

Fig. 4: Comparison of upwind strength in center of thermal for different weather models.

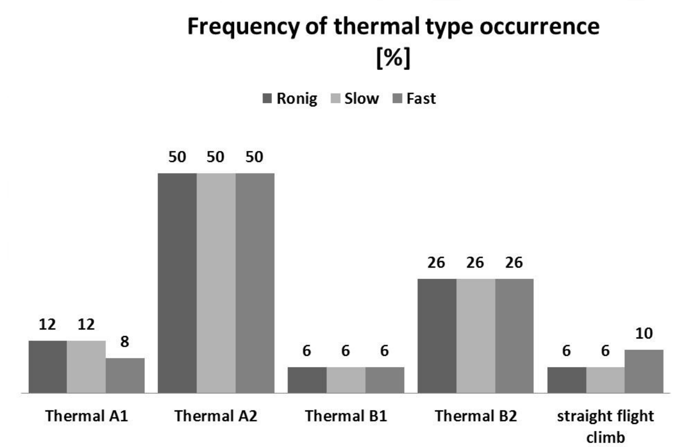

Fig. 5: Frequency of thermal type occurrence during a cross-country flight.

Figure 4 and 5 summarize the differences between the original weather model as defined by Ronig [9] and the two weather-models ("Slow" and "Fast") that were used in the context of the optimizations discussed in this paper. The use of two weather models with small differences in thermal strength and thermal type occurrence should help to identify the impact of the weather model selection on the optimization result.

Optimization results

In order to illustrate the influence of the target function on the optimization result, the most relevant parameter (the winglet height) has been set to be constant in the automated optimization process. A sweep of different heights has been set manually while all other free parameters defined in Fig. 2 have been optimized by the automated process chain. Therefore it is possible to illustrate the influence of the parameter winglet height on the different target functions, as shown in Fig. 6 to 8 .

The resulting geometries were then analyzed on the basis of

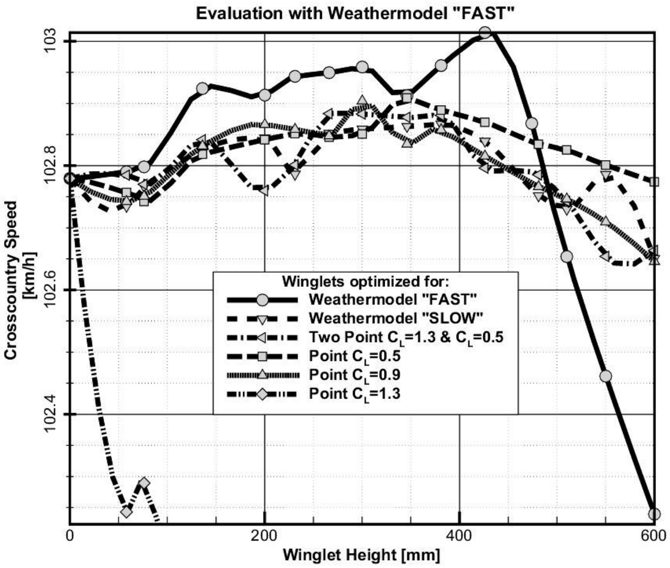

Fig. 6: Cross-country speed for model "FAST" of optimized winglets with varying height h.

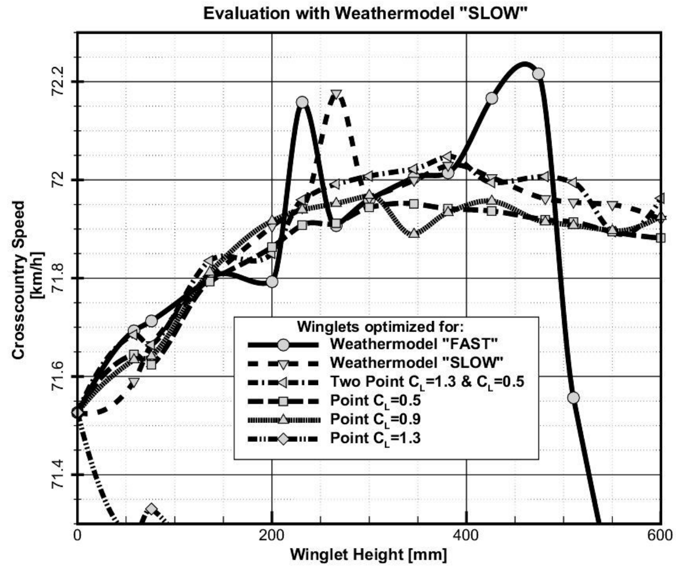

Fig. 7: Cross-country speed for model "SLOW" of optimized winglets with varying height h.

the different target functions, meaning that for Fig. 6 and Fig. 7 the mean cross-country speed for all optimized geometries were computed while in Fig. 8 the glide ratio of all those configurations at a lift coefficient of 1.3 are shown. Consequently the configurations optimized using the same target function as used for the analysis of the results are showing the best performance in the corresponding figure. As those performance results are just a rough indicator for the real performance, due to the lack of knowledge of what kind of weather the glider will really experience, their exact values are of minor importance. Of driving interest is the value of the parameter for which a target function maximum (or respective minimum) is predicted. In order to properly analyze the results, it would be nice to see a smooth curve having a clear maximum.

Figure 6 and 7 have quite bumpy curves with several local minima and maxima. If dealing with optimization task this is normally a good indication for having either a non-reliable analysis method (at least in the magnitude of the required precision), or looking at a non-converged optimization. As the convergence levels can be easily monitored and the feasibility of the applied methods will be demonstrated within the next section, where a comparison with flight performance tests are shown, the possibility of the optimizer finding a local instead of the global minimum must be considered as well. This assumption is supported by the fact that the simpler target functions (single C_L drag minimizations) provide smoother curves, which hints at a connection between complexity of target function and the likelihood of finding a local optimum. A respective test using an evolutionary optimization algorithm, which is very expensive but very likely (compared to "SUBPLEX") to find the global optimum is a still pending task. Nevertheless, the results are sufficient enough to analyze the connection between performance prediction for the optimized geometries and the influence of the target function onto those results.

Despite the analysis based on the weather models "FAST" and "SLOW" of the configurations optimized for a C_L of 1.3, all results are indicating a most beneficial winglet height between 350mm and 450mm. While for the good weather conditions,

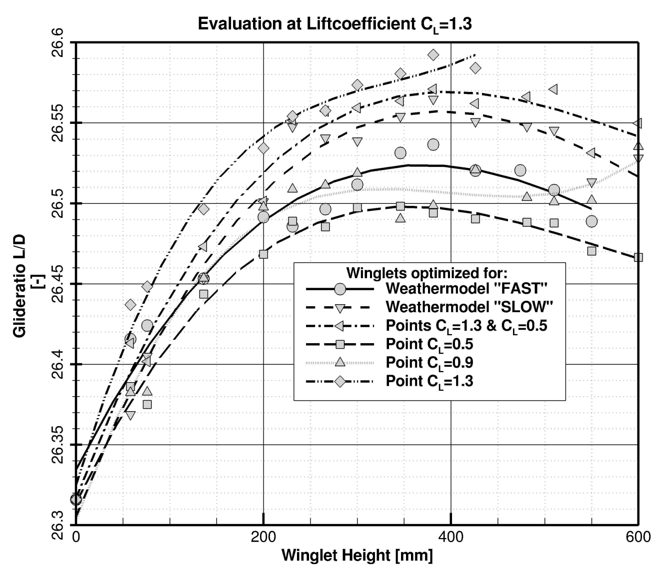

Fig. 8: Glide ratio L/D at lift coefficient $C_L = 1.3$ of optimized winglets with varying height h.

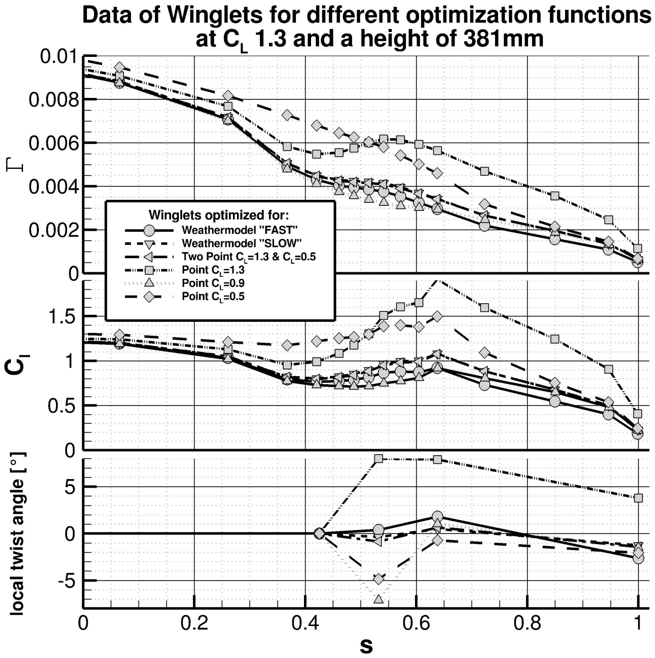

Fig. 9: Load distribution Γ, local lift coefficient c_l and twist angle variation ε vs. dimensionless true length s.

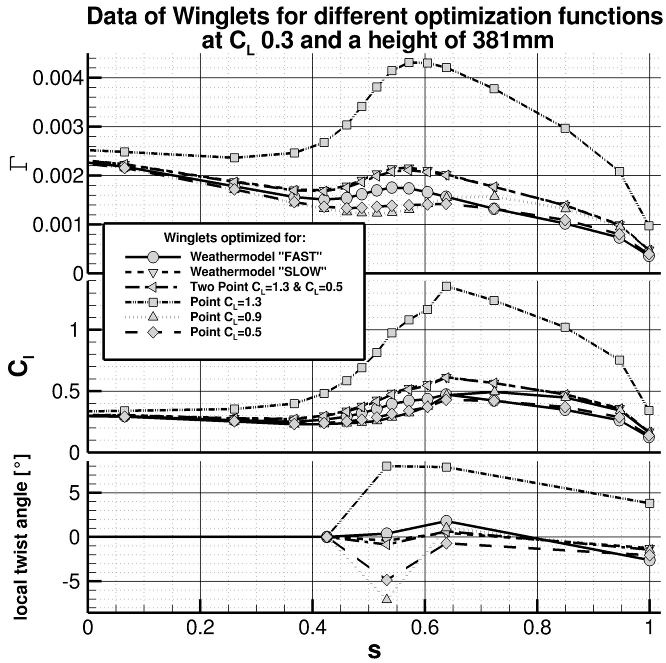

Fig. 10: Load distribution Γ, local lift coefficient c_l and twist angle variation ε vs. dimensionless true length s.

represented by weather model "FAST", the difference between a smaller winglet (e.g. 200mm) and a larger one (e.g. 350mm) is relatively small, the impact of size difference increases while expecting worse conditions as represented by weather model "SLOW" and single point optimization for "$C_L = 1.3$".

Analyzing the glide ratios of the different configurations for a C_L of 1.3 (Fig. 8), the only difference occurs for the configurations optimized using the "$C_L = 1.3$" target-function. The reason for this difference can be explained by analyzing the different load distributions resulting from applying the different target functions. Figure 9 and 10 show load distributions for a glider lift coefficient of $C_L = 1.3$ and $C_L = 0.3$ for a selected winglet height of 381mm. Additionally the local section twist and the local lift coefficients are shown as well (note: all quantities are plotted versus the dimensionless true length s, which starts at the wing to winglet joint, see e.g. in Fig. 11). The most striking fact is that the circulation, and therefore the local loading, is the largest for the configuration optimized with the target function "$C_L = 1.3$". This high loading is achieved by retwisting the sections instead of increasing the local chord-length, as can be seen in the graphs for local lift-coefficient-distribution and the local twist-distribution. This is a plausible result: The optimizer will try to achieve an optimal load distribution for minimum induced drag with, in order to keep friction based drag at a minimum, a surface area as small as possible. This might lead to a good result for the design point used, but can also cause trouble in off-design (C_L outside the section's "laminar bucket" with low profile drag) as has occurred in this case.

Comparison with flight test

Based on the optimization results, a new winglet shape was designed and fabricated. As a detailed RANS-based analysis was not performed and the "Lifting-Line" based chain cannot sufficiently resolve the highly three-dimensional flow in the transitional area from (horizontal) wing to (vertical) winglet, recent developments in how to design such a transitional area (Theurich, [10]) were considered in order to avoid drag penalties due to interference effects between wing and winglet. In Fig. 11 the newly designed winglet can be visually compared to the already existing SB 14 winglet, which was subsequently used as a reference for performance investigations. Mounted on the SB 14, the common testbed, both winglets were flight tested during the Idaflieg summer meet 2012.

The results of the flight performance tests are summarized in Fig. 12. In order to use these results for validation purposes, the SB 14 glider was recalculated in both configurations, equipped with the baseline winglets and the newly designed winglets, using the process chain described above. In the grey boxes within Fig. 12, the measured maximum performance deltas (optimized winglet vs. reference winglet) are compared to the calculated maximum performance deltas. The optimized winglet improves the performance of the glider at the speed of its best glide ratio and for lower airspeeds, as relevant for flying in thermals, while having small performance disadvantages for airspeeds that are relevant during interthermal cruise flight in good weather conditions. While the tendencies are predicted correctly by the computational model, the absolute values are generally under

Fig. 11: Baseline SB 14 winglet (left), the reference for the performance flight tests conducted, and the optimized SB 15 winglet (right).

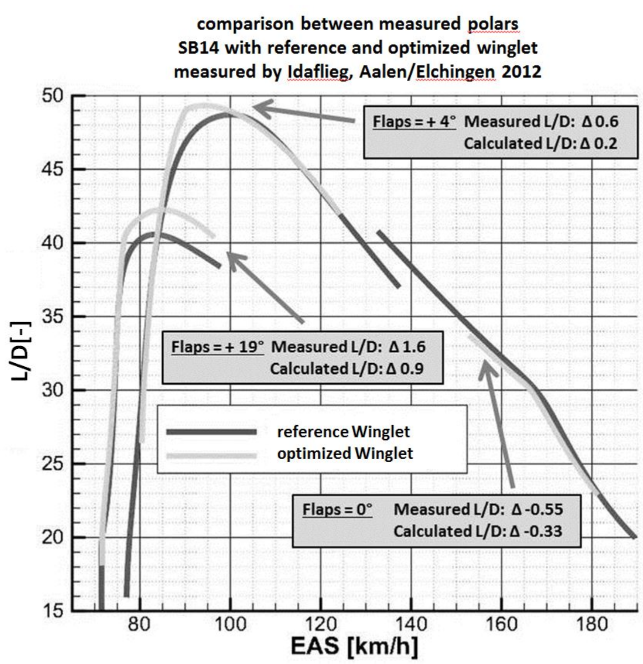

Fig. 12: Comparison of measured and calculated glider performance expressed by the glide ratio L/D versus airspeed.

predicted by the computational model. The most striking, not predicted, difference occurs for flap setting 4°, where the optimized winglet seems to perform significantly better at lower speeds. While there is no proven explanation for this result, it is assumed that the updated transitional area, i.e. the improved blending from wing to winglet, provides the most likely explanation for that difference. This assumption is based on the fact that, firstly, the airfoil sections, which might explain that kind of result as well, are identical for both winglets, and, secondly, both winglets have been built using similar manufacturing technologies. In the context of this paper, the results are illustrating the benefits and limits of the applied computational models. While the general influences of the applied geometry modification on induced and profile drag seem to be predicted reasonably well to successfully perform an optimization task, a precise prediction of absolute values for performance penalties or benefits cannot be expected. Therefore the method presented seems to represent a good compromise between accuracy and computational speed.

Conclusions

A computational chain for planform optimization has been presented and validated. It was shown that the chain is accurate enough to be used in the context of optimization, even if considering limits in representing all drag characteristics in full detail. Regarding the target function selection, the opinion of the authors is that a clever selection of lift coefficients for a multi-point optimization will provide a robust target function, while more complex target functions like, for example, a weather-model-based function might lead to complications with respect to the identification of the global minimum if applying a reasonably fast optimization model. A more detailed description of the optimization process and its results is given in a report written by Rohde-Brandenburger [11].

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