Aerodynamic Design of Winglets for a Standard-Class Glider

Udo Drebler

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SUMMARY

At the 1981 World Championships in Paderborn, the members of the French National team surprised their competitors with winglets mounted on their gliders. There was a lot of discussion about the effectiveness of this wing arrangement for high-performance gliders. This report describes the theoretical effect of different geometrical winglet parameters on the flight performance of an AS-W 19 glider. A promising winglet version was selected, built and measured in flight by the Akaflieg Braunschweig.

INTRODUCTION

At the tip of the wing the pressure differences between upper and lower surface can equalize and cause an airflow tending outboard under the wing, around the wingtip, and inboard over the wing. Behind the moving wing these crossflows roll up to form two lines of counter rotating vortices. The kinetic energy in the vortices represent the work of moving the wing against the drag.

If the build-up of the vortices can be reduced, the induced drag will be lessened. This happens, for example, in the so called ground-effect when a wing approaches the ground, or during formation flight of migrating birds on long distance trips.

Similarly, a small wing attached approximately perpendicular to the plane of the wing at the wingtip can impede the crossflow and thus reduce the strength of the trailing vortices. Unlike conventional flat end plates, winglets are carefully designed for the local flow conditions in order to achieve the benefits of reduced induced drag with a minimum penalty due to additional skin friction, or drag due to flow separation. Because the ground clearance of the AS-W 19 wing should not be reduced, only winglet configurations above the wing tip were examined.

The importance of the induced drag is demonstrated in Fig. 1. The AS-W 19 total drag coefficient and the coefficient of drag excluding induced drag are shown.

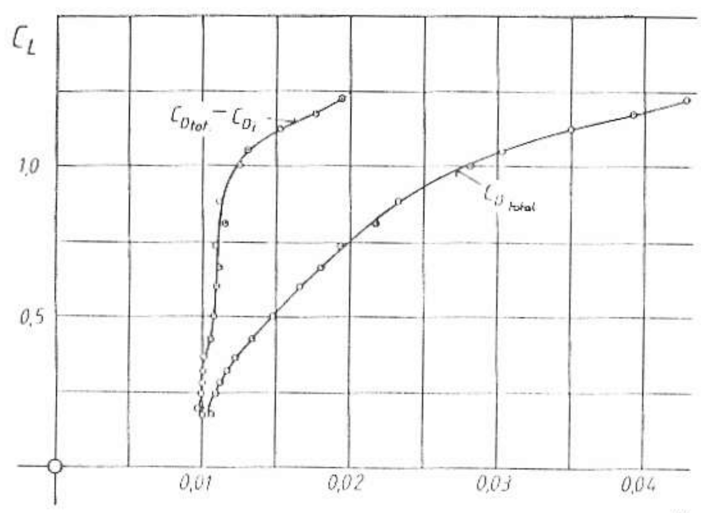

Fig. 1 Total drag and total drag minus induced drag of the ASW-19.

At high lift coefficients, the induced drag contributes more than 50% to the total drag, while its influence shrinks at high flying speeds to about 5% at $C_L = 0.2$. Accordingly, the greatest improvements from winglets are to be expected at high lift coefficients, for example, during thermaling and at low cruising speeds. At lower lift coefficients, the additional skin friction drag gains importance, and below a certain lift coefficient outweighs the favourable effect of the winglets on the induced drag.

THE WING WITH WINGLETS

To get an idea of how the winglets affect the lift distribution of the wing, Fig. 2 shows the optimum circulation distribution of a 15-m wing with 1-m high winglets compared to an ellipitical distribution, which is best for the wing without winglets. In addition, the local lift coefficients and angles of incidence necessary to achieve this circulation distribution with the AS-W 19 wing are shown for a lift coefficient of $C_L = 1.0$.

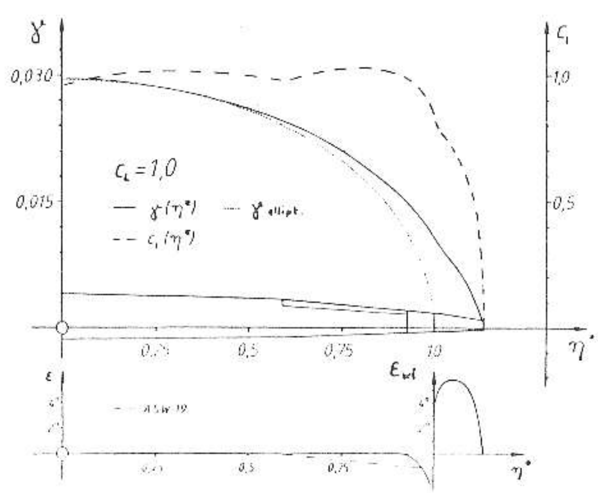

Fig. 2 Optimum circulation distribution for a 15 m wing with 1 m high winglets and local lift coefficients and angles of incidence to achieve this distribution with the ASW-19

The optimum circulation distribution of the winglet configuration does not differ significantly from the dotted line denoting the ellipitical distribution in the inner part of the wing. Approximately at midspan, however, the optimum winglet circulation distribution departs from the elliptical distribution and maintains a certain level of circulation at the wingtip, which is then reduced over the length of the winglet to zero at the winglet-tip. The shape of this optimum curve is independent from the lift coefficient of the aircraft. Thus, the optimum circulation for the winglet depends on the circulation of the wing, but the angle of incidence of rigid winglets can only be optimized for one lift coefficient of the wing.

For a winglet with the same chord length at the winglet-root as the wingtip chord, and a winglet taper-ratio of $\lambda_{wl} = 0.5$, reasonable angles of incidence of the winglet will be in between $\epsilon_{wl} = 2^0...5^0$. The required angle of incidence of the retrofitted wing does not differ significantly from that of the original AS-W 19 wing. Also, airfoils capable of achieving a high maximum lift coefficient in the outer portion of the wing make the AS-W 19 a suitable aircraft for winglets, providing good stalling characteristics, and offer the possibility of a higher maximum overall lift coefficient of the aircraft.

The winglet circulation should be produced with a minimum amount of skin friction drag. To keep the winglet surface small, an airfoil is needed which is appropriate for low Reynolds numbers and high lift coefficients. Also, the superposition of the pressure gradients of the airfoils of the winglet and the wing in the intersection region should not lead to higher airfoil drag or flow separation. This requires relatively thin. chambered airfoils for the winglets. From the 'Stuttgart Airfoil Catalog' the FX 60-126 section, already used as the outboard wing section of the AS-W 19, was selected. It exhibits a relatively high maximum lift coefficient of $c_{Lmax} = 1.5$ at Re = 500,000 and moderate chordwise pressure gradients in the rear of the airfoil.

CALCULATION PROCEDURE AND RESULTS

The following calculations of the flight performances of the different winglet configurations are based on a measured polar of the AS-W 19 from 1976. Because the winglets don't influence the drag of the fuselage and the inner parts of the wing, the following calculation is adequate: the measured total drag of the AS-W 19 is reduced by its induced drag and the airfoil drag of the outer wing, to form a so-called basic drag level of the AS-W 19. A potential flow program calculates the induced drag of the winglet version. Based on the local lift coefficients and Reynolds numbers of the outer wing and winglets, airfoil drag is computed and added to form the total drag.

The interference drag of the wing-winglet-junction is suggested to be zero because a good fairing should be planned.

Since the speed polars of the different winglet configurations are quite similar, a few characteristic points of the polar are selected to compare the sink-rates or glide-ratios. All flight-performances are based on the lowest possible wing loading of $G/S = 310\ N/m^2$. As parameters representative of the range of high lift coefficients (thermaling and low cruising speeds), the minimum sink-rate and the maximum glide-ratio are selected. Improvements achieved here mainly affect the average cross-country cruising speed in weak thermal conditions. For the upper speed range used in strong weather conditions, the sink-rate at 150 km/h, corresponding to lift coefficient of $c_L = 0.3$, is considered representative.

INFLUENCE OF THE WINGLET HEIGHT ON THE FLIGHT PERFORMANCE

Of the parameters examined, the height of the winglets, h_{Wl}, exhibited the most important influence on the lift distribution of the wing. The higher the winglet, the greater is the equivalent wingspan and the lower the induced drag. On the other hand, skin friction drag will increase with the size of the winglets.

Fig. 3 shows the induced drag factor, K, of the AS-W 19 with winglets varying from h_{Wl} = 0.0 to 3.00 m.

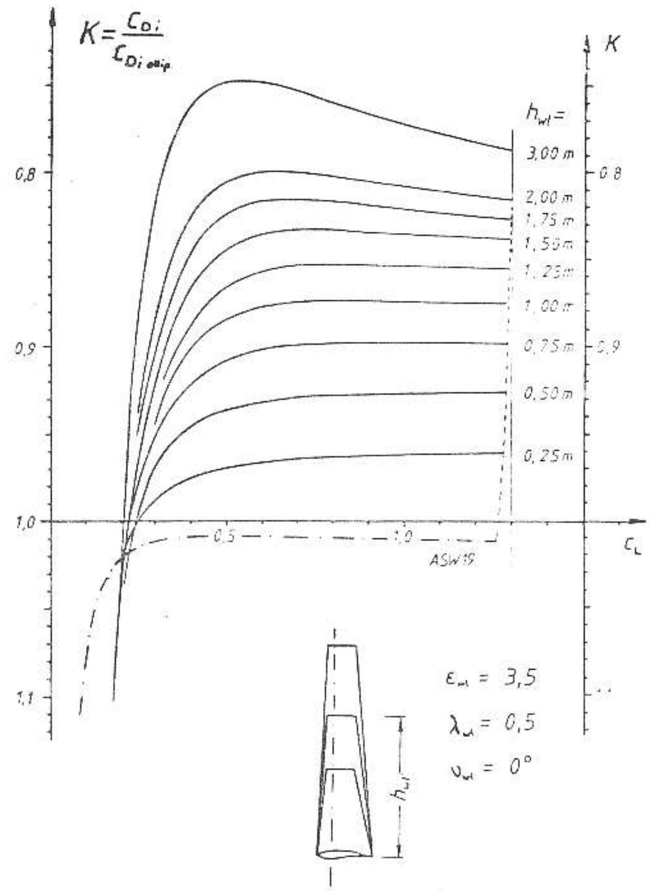

Fig. 3 Induced drag of the ASW-19 with winglets of different heights.

As expected, the induced drag diminishes with increasing winglet height. Allowing for the additional skin friction drag caused by the winglets, the flight performance of the AS-W 19 has been computed and plotted in Fig. 4, together with performance levels of the regular AS-W 19 and a fictitious AS-W 19 with 17-m wingspan. The minimum sink-rate of the AS-W 19 can be reduced with 2.5 m high winglets by 4.3 cm/s to 58.2 cm/s. Even if structural and flutter problems are neglected, such high winglets would not be reasonable for the whole speed range used in a cross-country flight. At the speed corresponding to the maximum glide-ratio, the best results (an increase of L/D_{max} = 1.6) are achieved with 2.0 m high winglets. The optimum winglet-height decreases with rising speed.

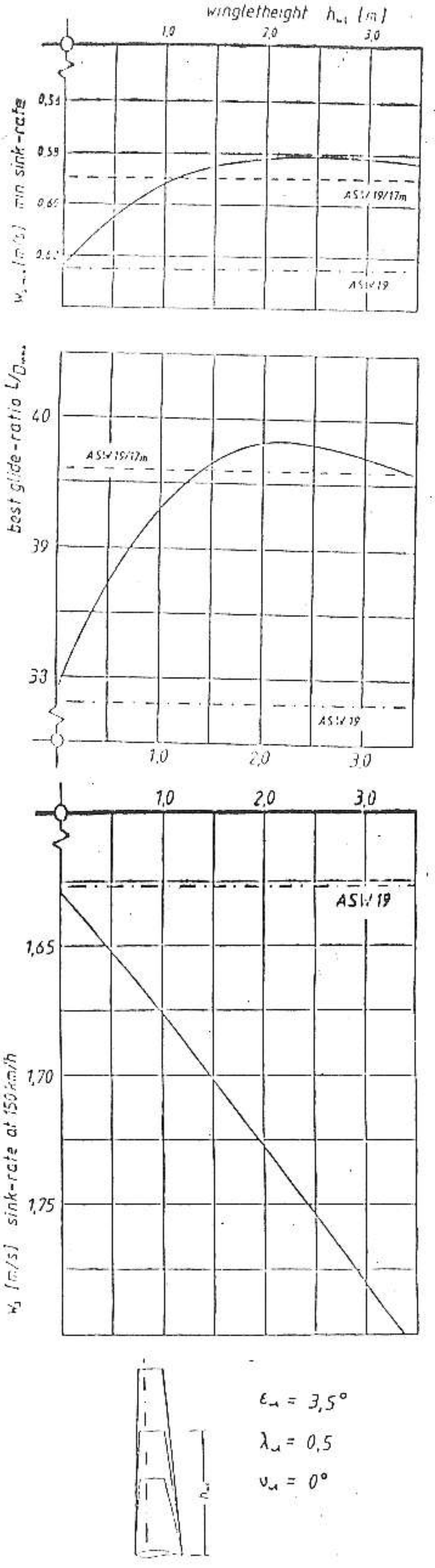

Fig. 4 Flight performances of the ASW-19 with winglets of different heights.

At about 115 km/h, corresponding to a lift coefficient of $c_L = 0.5$, the optimum winglet height is zero. At higher speeds any winglet configuration produces more drag than the regular AS-W 19. Thus the sink-rate at 150 km/h increases in direct proportion to the height of the winglets.

As a good compromise between the benefits at low speeds and the losses at high speeds, 1-m high winglets were selected. At the minimum sink speed these winglets achieve 77% of the gain of the 2.5 m high winglets, while at high speeds only a moderate loss is incurred.

INFLUENCE OF THE WINGLET'S ANGLE OF INCIDENCE ON THE FLIGHT PERFORMANCE

As already mentioned, the optimum winglet circulation depends on the circulation of the wing; for low speeds, higher lift coefficients on the winglet are necessary than for high speeds. Given the winglet-chord length, the circulation can be adjusted by the winglet angle of incidence.

For 1-m high winglets with a taper-ratio of $\lambda_{wl} = 0.5$ and different angles of incidence, the induced drag of the AS-W 19 is shown in Fig. 5. High

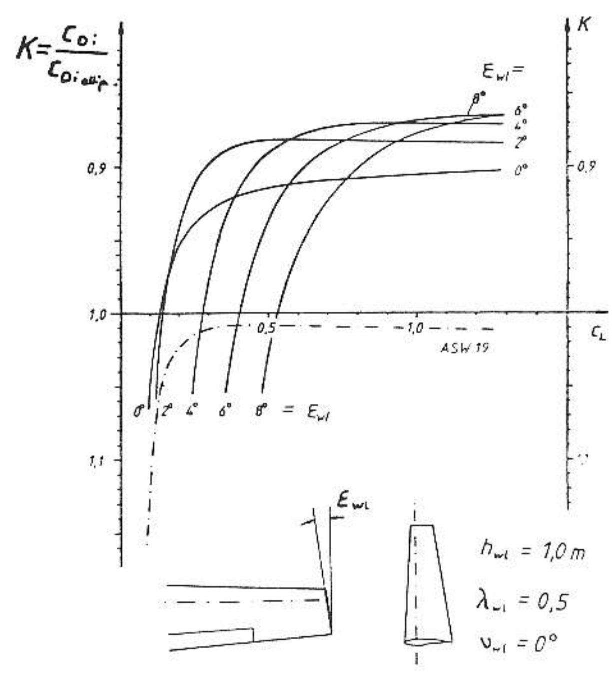

Fig. 5 Induced drag of the ASW-19 with 1-m high winglets of different angles of incidence.

angles of winglet incidence cause low induced drag at high lift coefficients. At low lift coefficients the lift distribution is so disadvantageous that even at relatively high lift coefficients, for example at $c_L = 0.5$ for $\varepsilon_{wl} = 8^{o}$, the induced drag of the winglet configuration is higher than that of the basic AS-W 19. On the other hand, winglets with low angles of incidence, designed for low lift coefficients, do not perform well at high lift coefficients. In the FAI-racing-class this problem could be solved by a flap on the winglet; in the Standard Class, however, this would be outlawed as a lift influencing device.

The flight performance of these winglet configurations is shown in Fig. 6. The optimum angle of winglet incidence is close to the incidence for the minimum induced drag. But at high lift coefficients the rapid increase in skin friction drag shifts the optimum toward lower angles of incidence. For the whole range of cross-country flight speeds, an angle of incidence of $\varepsilon_{wl} = 3.5^{o}$ appears to be a reasonable compromise.

INFLUENCE OF WINGLET CANT ANGLE

While until now only vertical winglet configurations were examined, there is the possibility of canting the winglets without exceeding 15-m wingspan by shifting the winglet root inboard. At the same winglet height, such an arrangement has a smaller wetted surface and thereby less skin friction drag than a vertical winglet. Furthermore, the angle of attack of canted winglets increases with higher wing angles of attack. This could, especially at high inclination angles of the winglet, lead to the desired adaption of the winglet circulation to the circulation of the wing.

The induced drag of winglet configurations with different cant anlges is shown in Fig. 7. For any lift coefficient the induced drag rises with the inclination angle of the winglet. A well balanced improvement for all lift coefficients by a higher cant angle does not appear possible.

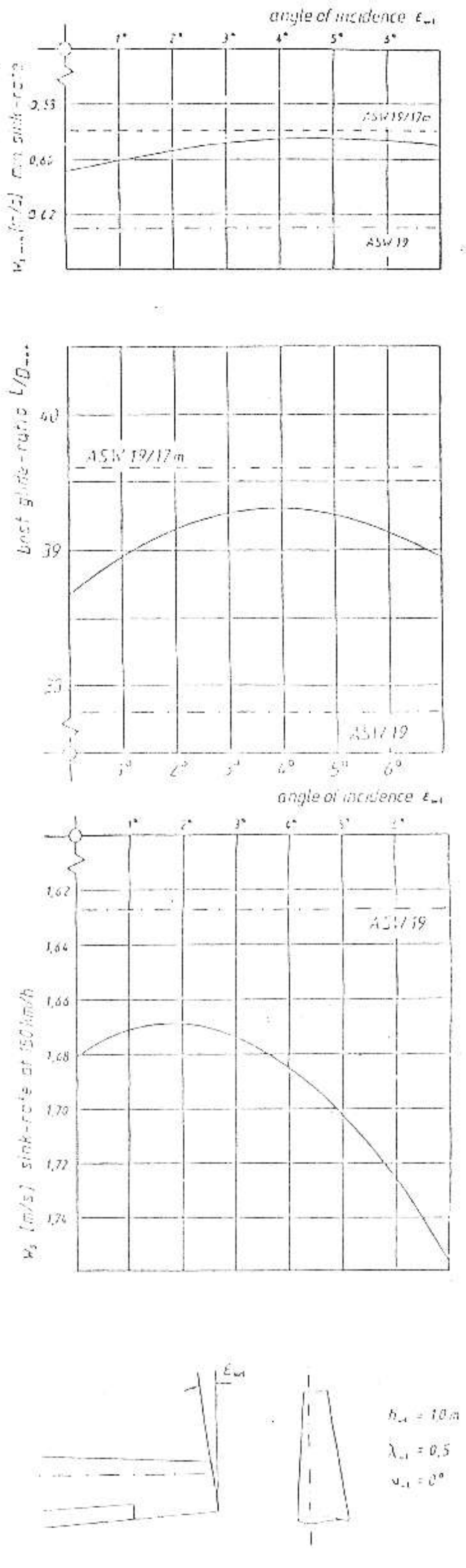

Fig. 6 Flight performances of the ASW-19 with 1 m high winglets of different angles of incidence.

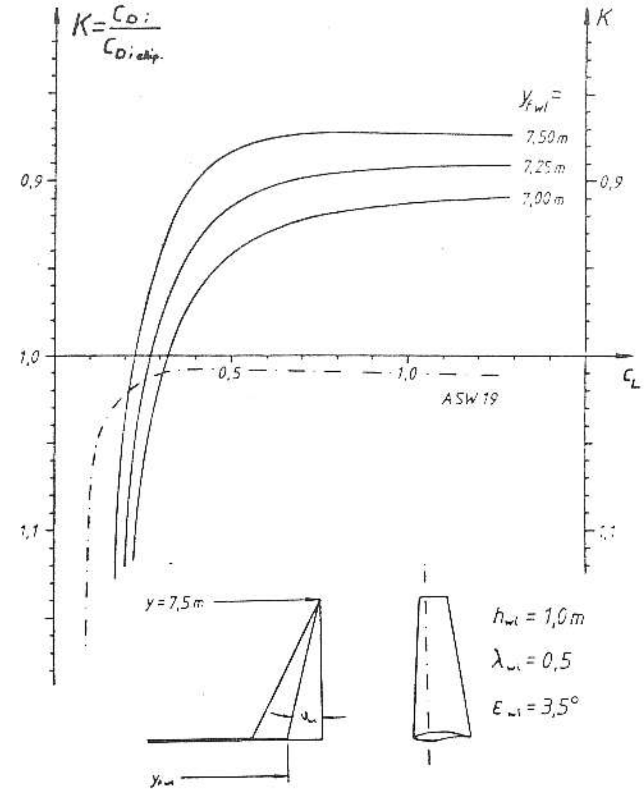

Fig. 7 Induced drag of the ASW-19 with 1 m high winglets of different angles of incidence.

The flight performances shown in Fig. 8 demonstrate that, for high lift coefficients, the induced drag of canted winglets increases faster than the skin friction drag, associated with the wetted surface area, decreases. Only at high speeds do inclined winglets appear to be advantageous. But, if the inclined winglets are compared with vertical winglets of the same wetted surface area, smaller vertical winglets appear to be superior at all lift coefficients. Also, the smaller vertical winglets have smaller moments of inertia about the wing spanwise axis which determines, in this case, the possibility of flutter.

VARIATION OF OTHER WINGLET PARAMETERS

A further possibility of reducing winglet area and thereby skin friction drag is to increase the winglet aspect ratio. In order to maintain the winglet circulation with smaller chords, the lift coefficients, and thus the angles

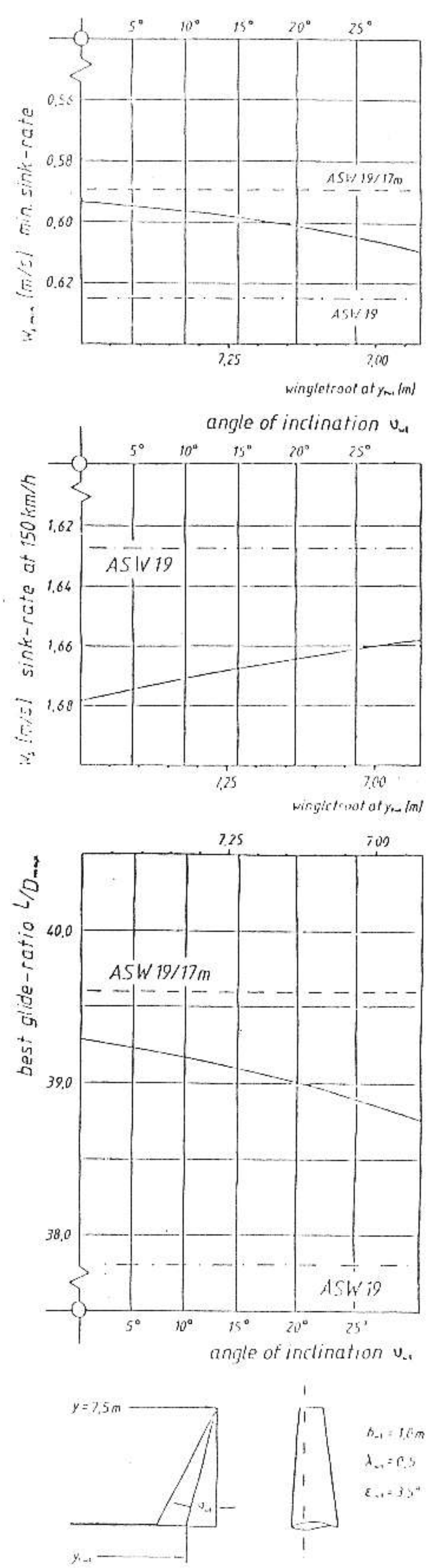

Fig. 8 Flight performances of the ASW-19 with 1 m high winglets of different angles of inclination.

of incidence of the winglet, need to be increased. Decreasing Reynolds numbers and increasing lift coefficients brings the airfoil close to its maximum lift coefficient, which is associated with extraordinary high profile drag coefficients. Also, this overall improvement in induced drag decreases with increasing lift coefficients of the winglet. Therefore, no significant improvement is achieved by the reduction of winglet-chord length. A winglet airfoil with other lift-drag-characteristics would lead to a slightly different optimum chord length.

Also, a variation of the winglets' taper-ratio does not seem to significantly affect the flight performance. At high lift coefficients, the reduced skin friction drag of winglets with a high taper-ratio is compensated by a higher induced drag. Only at high speeds would high taper-ratio winglets offer a small advantage.

FINAL WINGLET SELECTION

Choosing the right aspect ratio, as well as a proper taper-ratio, was influenced by the need of maintaining, particularly at low speeds, sufficient difference between the actual local lift coefficient and the maximum possible lift coefficient of the airfoil. This stall margin is necessary to prevent flow separations through the superimposition of the pressure gradients of wing and winglet airfoils and to allow for slight side slip angles.

The final winglet configuration was especially designed to provide a constant difference between the maximum obtainable lift coefficient of the winglet airfoil and the local lift coefficients encountered by the winglet at the maximum lift condition for the aircraft.

The wing-winglet-fairing is formed by a radius of r_{Wl} = 200 mm with such a distribution of the angles of incidence in the radius region that a local lift coefficient of c_l = 1.2 is not exceeded.

The resulting distribution of the local lift coefficients over the folded out wingspan is shown in Fig. 9, in comparison to the regular AS-W 19 for the particular maximum lift coefficients. The stall characteristics are not affected by the winglets; this was proved by the flight tests. Also, in the wing-winglet-fairing region no flow separations were observed during normal flight maneuvers. The calculated glide performances are shown in Fig. 10 as a function of the air speed.

The theoretical calculations were confirmed by flight measurements of the AS-W 19 with and without winglets as shown in Fig. 11.

The influence of the winglets on the

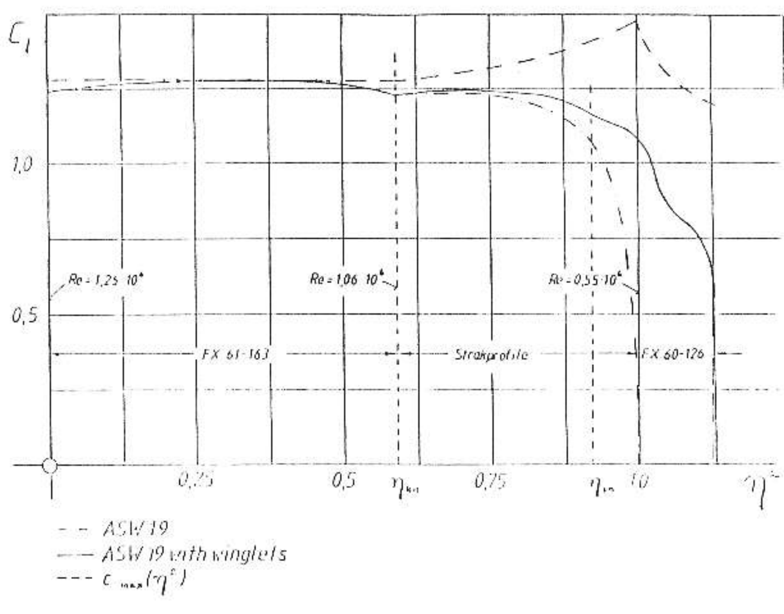

Fig. 9

Local lift coefficients of the ASW-19 and the ASW-19 with winglets at their particular maximum lift coefficients.

flight mechanic stability derivatives are based on the fact that the wing with winglets is similar to a wing with more dihedral. The yaw induced rolling moment of the AS-W 19 is doubled by the winglets, which increases the effectiveness of rudder control during circling. Furthermore, winglets can produce a direct side force which allows stronger side slips for landing. The additional weathercock stability due to the winglets is not significant.

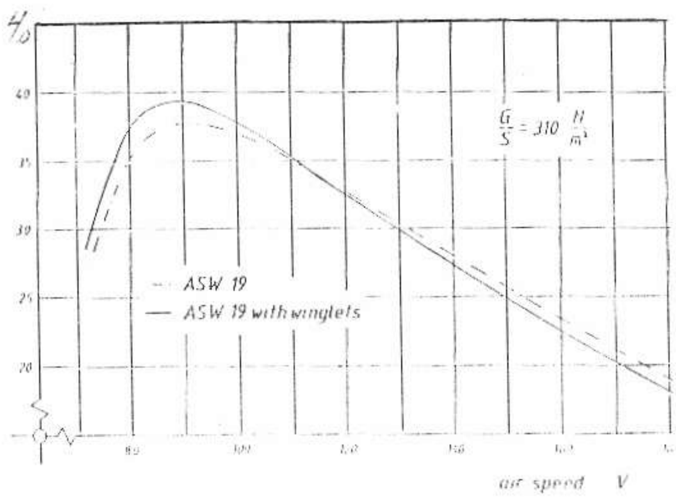

Fig. 10 Calculated flight performances of the ASW-19 with and without winglets.

CROSS-COUNTRY CRUISING SPEEDS

To weigh the advantages of winglets at low speeds against the disadvantages at high speeds, the thermal and cross-country flight models of Horstmann and Quast are used. The hypothetical flight consists of circling in four different types of thermals and corresponding cruise-flights.

The circling performance of the AS-W 19 with and without winglets is shown in Fig. 12

The reduced drag at low speeds and the higher maximum lift coefficient of the winglet aircraft permit either 5 to 10 cm/s less sink-rate for the same circle radius. Or at the same sink-rate, it will permit a 1 to 2-m narrower circle, allowing the pilot greater gliding range. In addition, the gradients of the four hypothetical thermal types are

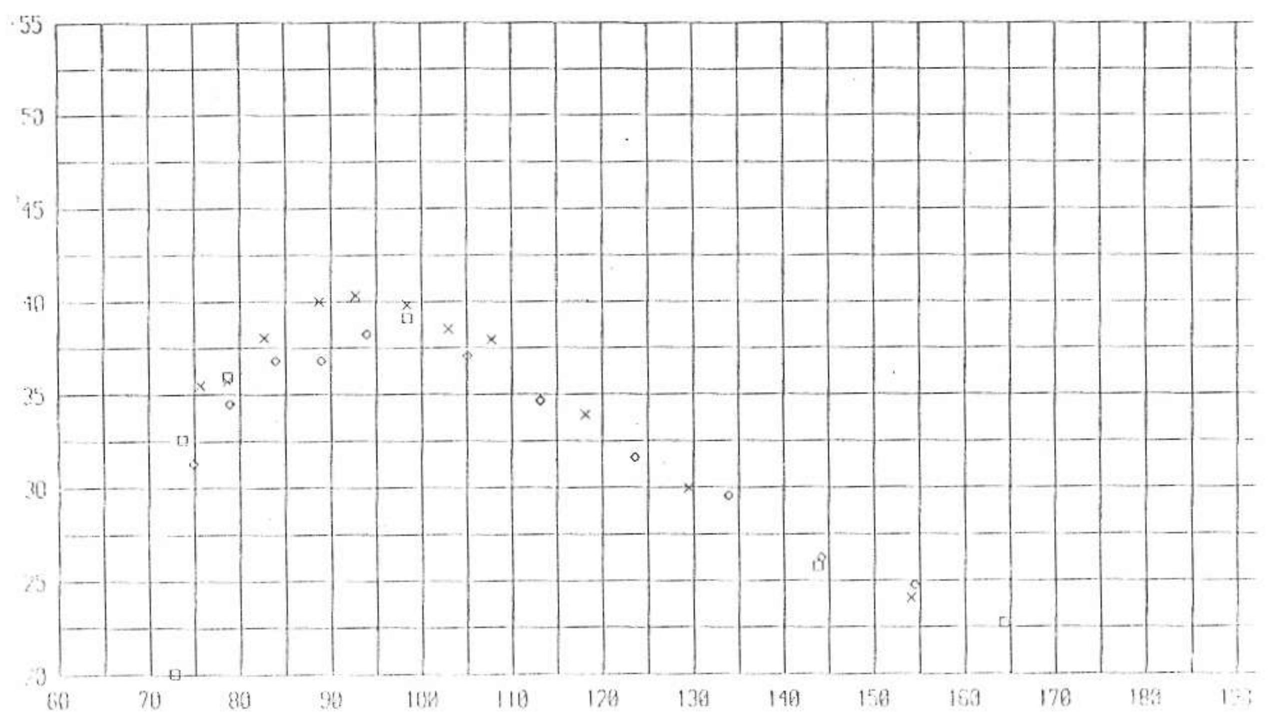

Fig. 11 Measured flight performances of the ASW-19 (◦) and the ASW-19 with winglets (□ ×).

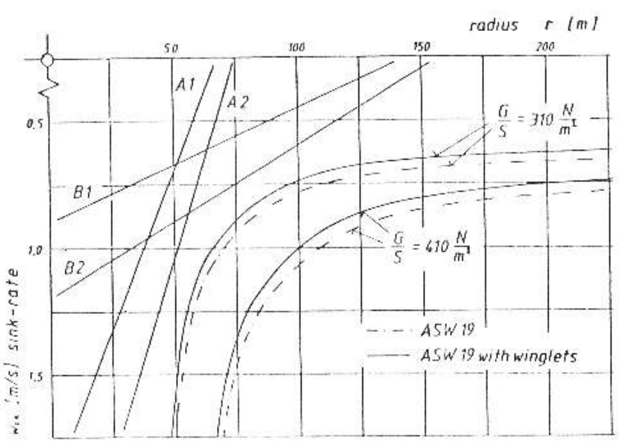

Fig. 12 Circling performance of the ASW-19 with and without winglets.

shown to visualise the significant parts of the circling polar.

The resulting cross-country speeds in the four thermal types are shown in Fig. 13 as a function of the wing loading.

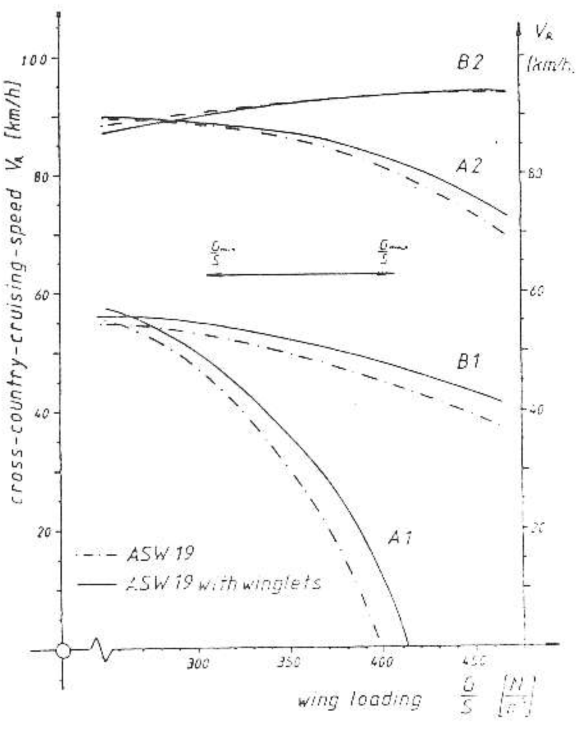

Fig. 13 Cross-country cruising speeds of the ASW-19 with and without winglets over a range of wing loadings in four different types of thermals.

At the particular optimum wing loading, the AS-W 19 with winglets is faster in all thermal types than the regular AS-W 19. The best results are achieved in the narrow, weak A1-type thermals. But even in the strong, B2-type thermals, there is still a slight improvement. Generally, winglets are better in combination with high wing loadings, because then the cruise portion is not only flown at higher speeds, but also at higher lift coefficients where induced drag is more significant. This is important since many competition pilots tend to fly at higher wing loadings than postulated in this model. Also, a lot of pilots conduct their cruise-flights at a speed lower than the MacCready speed in order to reach a distant thermal and thus fly in a speed range more advantageous for winglets. Further, in special weather situations, not considered in the hypothetical model, like 'parking' to wait for redeveloping thermal activity or crossing an area without any thermals, winglets prove superior.

CONCLUSION

Theoretical calculations verfied by flight measurements show performance improvements for a 15-m sailplane by addition of 1-m high winglets at lift coefficients above $c_L = 0.5$. Winglets reduced the minimum sink-rate of the AS-W 19 by 3.3 cm/s, improved the maximum glide-ratio by 1.6 points and increased the maximum lift coefficient of the aircraft by $c_{L max} = 0.03$. The performance losses below the break-even lift coefficient ($c_L = 0.5$) are moderate, so that an overall improvement, measured in terms of cross-country cruising speeds, can be achieved.

Generally, it should be noted that it is only reasonable to use winglets on gliders with a limited wingspan. A 17-m aircraft, which probably would be easier to manufacture, is far superior to a 15-m aircraft with winglets.