Aerodynamic Design and Cross-country Flight Performance Analysis of Diana-2 Sailplane

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Presented at the XXVIII OSTIV Congress, Eskilstuna, Sweden, 8-15 June 2006

Abstract

The aerodynamic design philosophy and computational analysis of cross-country flight performance of Diana-2 sailplane in different thermal conditions are presented. To address the second issue, a continuous spectrum of thermal models is created. For specified thermal model (thermal strength vs distance from core center, interthermal descent, length and strength of cloud streets), the sailplane mass and aerodynamic characteristics optimum flight parameters (circling speed and bank angle, interthermal glide speed and speed in cloud streets) is found applying optimization technique. Finally expected cross-country speed for different thermal conditions and water ballast weight, as well the optimum water ballast amount, can be predicted. The main goal of the analysis is the optimization of sailplane parameters and helping pilots make decisions regarding optimum balasting technique in flight. An estimation of the influence of bugs and rain on the sailplane aerodynamic characteristics is also presented.

Introduction

The SZD-56 Diana sailplane was designed in 1989. Its first flight was in 1990. SZD's chief engineer, Bogumil Beres, designed the ‘56, which was quickly acclaimed for its unique wing structure and other innovative features. The sailplane has many unusual features, e.g. very light structure (175 kg empty weight), very thin (13%) high aspect ratio (27.6) monocoque wing. Unaffected by a massive spar, the '56 wings hold their precise, unwavering contours year after year. Additionally, the spar-less design leaves extra room for ballast: the '56's wet wings hold 160 liters. In the late 80's and early 90's, glider aerodynamics progressed quickly thanks to both extensive wind tunnel experimental work and the development of advanced computational methods in fluid dynamics. SZD Bielsko-Biala did not have these kinds of resources at that time. Other gliders built 3 to 6 years after the Diana had a chance to use all these new tools and ideas, which allow for reducing the profile drag and lowering adverse aerodynamic inference. Because of these advantages, these newer gliders achieved much better performance. Consequently, Diana, one of the most technologically advanced sailplane but equipped with less modern aerodynamics (a Wortmann type, based on 70’s technology, free transition type airfoil), fell into background. In 2003 the decision was made to design new, advanced aerodynamics for Diana. In the case of high performance racing class sailplanes, the wing produces most of the drag. Because of this fact and the expected costs, modernization was restricted mainly to the design of a new wing and minor fuselage and undercarriage modifications.

The main objective of modern sailplane design is the maximization of overall performance that can be measured by cross-country speed for specified thermal conditions. To address such a problem, a mathematical model of cross-country flight must be established. Such an approach must take into account the thermal model, sailplane aerodynamic characteristics (dependent on various design parameters and “aerodynamic technology”), and the mass (water ballast amount). The problem is very complicated (especially weather and thermal conditions), so only a very simplified approach can be used. Real design process is iterative in nature. Hence, subsequent modifications of design parameters and aerodynamic solutions, estimation of resulting efficiency are completed and the final design choices are made.

The presented results describe final configuration of the Diana-2.

Cross-country performance analysis

A typical cross-country flight pattern is shown in Fig. 1. It includes circling in a thermal, interthermal descent, and cloud streets. Thermal strength (including diameter and vertical velocity distribution), interthermal descent strength r_d (expressed as a fraction of max. thermal strength), and the cloud street’s relative length rl_{cs} and strength r_{cs} (expressed as a fraction of max thermal strength) are the parameters describing thermal conditions. The specification of thermal characteristics is the most challenging problem as they depend on a great number of factors (weather conditions, geographical region, ground features, altitude, time, etc.) and are in principle governed by stochastic rules. A very limited amount of measured data is available in the literature, making this problem even more difficult. Horstmann[1, 2] models are probably the most realistic approach. They include four standard thermal profiles: combination of strong (2) and weak (1) and wide (B) and narrow (A) thermals. A linear variation of the vertical velocity distribution outside a 60m-radius thermal core is assumed. The direct application of those models to the current problem is, unfortunately, not possible as continuous spectrum of thermal strength is required.

A continuous family of thermals based on the assumption of a linear interpolation between the Horstmann models was created. Three thermal families are specified and used, A: narrow, B: wide, C: middle thermal. The lift distribution varies linearly between 60m and *R_max*, where its value is zero. A parabolic lift variation is assumed inside the thermal core. The rate of climb for a particular thermal shape, specified sailplane mass, and the aerodynamic characteristics can be specified as:

$$w_C = w_T - w_{SINK} \tag{1}$$

where the thermal lift at a specified circling radius and sink velocity can be expressed as:

$$w_T = w_T\left(THERMAL\_MODEL,\ w_{T0},\ R_{CIRC}(V_{CIRC}, \varphi_{CIRC})\right)$$

$$w_{SINK} = w_{SINK}\left(V_{CIRC}, \varphi_{CIRC}, MASS,\ AERODYNAMICS\right) \tag{2}$$

The final equation for altitude balance takes form of:

$$(w_T - w_{SINK}) \cdot t_{CIRC} = (w_{SINK} + w_d) \cdot \frac{L - L_{CS}}{V_d} + (w_{SINK} - w_{CS}) \cdot \frac{L_{CS}}{V_{CS}} \tag{3}$$

The average cross-country speed depends on the following:

$$V_{CC} = f\big(THERMAL\_MODEL,\ w_{T0},\ r_d,\ r_{CS},\ rl_{CS},\ MASS,\ AERODYNAMICS,\ V_{CIRC},\ \varphi_{CIRC},\ V_d,\ V_{CS}\big) \tag{4}$$

It is seen that net rate of climb depends on the thermal model, thermal strength w_{T0}, sailplane mass, aerodynamic characteristics, circling speed, and bank angle. Similarly, the average cross-country speed depends on all above parameters and, additionally, on the weather model (r_d, rl_{CS}, r_{CS}), speed at interthermal glide, and along cloud streets. For a specified weather model, thermal strength, mass, and aerodynamic characteristics of the sailplane, the optimum flight and circling parameters, as well as final average cross-country speed, can be easily found using nonlinear programming methods. Such modeling of gliding tactics is equivalent to that of MacCready, which is not the one actually applied by pilots due to relatively low value of probability of arrival. Additional mathematical analysis shows, however, that reasonable modifications to the MacCready rules have little influence on the final average cross-country speed – increasing significantly the probability of arrival[3, 4]. This justifies the treatment applied in the present work.

Climb performance in a thermal

Equation (3) indicates that improvement in cross-country performance can be directly achieved by better climb performance in a thermal. Computational correlations between the lift coefficient in circling, the radius of circling (and bank angle), and climb performance for maximum sailplane weight using two thermal profiles (of the same strength: w_{T0} = 4m/s) are presented in Fig. 3. It is seen, that the higher the available lift coefficient the more efficient thermal climb. More in-depth analysis indicates that a higher C_L in circling leads to lower optimum circling speed, lower bank angle and radius, higher net rate of climb, and higher average cross-country speed. We also can assume that low speed (high C_L) characteristics are relatively independent on high speed (low C_L) characteristics – at least for flapped wings. Figure 4 shows the expected climb ratio and average cross-country speed for maximum weight as a function of thermal strength for wide and middle thermal models. For the cases presented in Fig. 3, the climb improvement at optimum circling due to increased C_L from 1.3 to 1.5 is about 0.1m/s (wide thermal) and 0.2m/s (middle thermal), while the increase in expected average cross-country speed (more details on that in the following chapters) is about 2 and 4 km/h, respectively. The improvement for narrow thermals (A) is much higher (0.4 m/s and 10 km/h). It is clear that enabling circling at higher C_L significantly improves overall glider performance.

Modern, low-drag glider airfoils[5] have specific features. The lift characteristics at higher angles of attack have a local decrease of lift with increasing angles of attack (has a local minimum). The reason for such features is the abrupt forward movement of transition point along the upper surface and the thickening of boundary layer. According to an unpublished paper presented at OSTIV Congress in 2003 by A. Dushyn and L. L. M. Boermans ("Sailplane climb performance in thermals due to dynamic effects"), this local minimum in the lift curve can have significant influence on sailplane's behavior during entering thermal and flying in a turbulent thermal.

The situation is explained schematically in Fig. 5. If an angle of attack during circling is near local maximum of C_L (and close to the upper limit of the low drag bucket) a downward gust (one that decreases the angle of attack) leads to some loss of lift and some loss of altitude. An upward gust (one that increases the angle of attack) leads to additional lift in the case of a monotonic lift-angle of attack relationship, and an increase in speed and climb rate. However, in the case when the lift curve has a local minimum as noted, an increase in angle of attack leads to a loss of lift and altitude. A variation of angle of attack due to a gust can reach up to 5 deg. Thus, there can be a significant problem in circling at such a value of the lift coefficient due to both the loss of climb efficiency and the danger of stall. This means that circling at lower C_L is necessary for efficiency in case of an airfoil with lift characteristics containing a local minimum.

Wing sections

Basic airfoils designed for Diana-2 wing have characteristics slightly different to more typical sailplane airfoils. Comparison of one of the Diana-2 airfoils to another typical modern sailplane wing section is presented on the Fig. 6. The main properties of new airfoil are monotony of the lift characteristics and a much higher maximum lift coefficient. Moreover, there is much less sensitivity to bugs and rain. That problem is related not only to an increase of drag in such conditions but also to significant loss of lift due to separation, especially at larger flap deflections. Wet conditions were computational simulated by forcing transition at 7% of the airfoil chord and specifying a low value of the critical amplification factor. It is observed in the figure, both problems have been significantly reduced in the case of the present design. The main drawback of the new airfoil is the reduction of low drag-bucket width and a higher sensitivity to the incorrect flap settings in flight. However, minimum profile drag is expected to be slightly lower than for typical modern glider airfoils. The airfoil is equipped with a 17% chord-performance flap with a deflection range of -2^0 to $+28^0$. The laminar flow extends to 70-75% of the upper surface (flaps down and higher CL conditions) and 92% of the lower surface (flaps up and low to moderate CL). The transition on the lower surface is enforced by a pneumatic turbulator in order to prevent laminar separation. The characteristics of the airfoil suggest that safe and efficient circling at a C_L of about 1.5 (flaps deflection $+21^0$) is possible.

Such characteristics of the airfoil have been obtained do to a unique pressure distribution along the chord (with lower pressure gradients in recovery region and reduced stability of laminar boundary layer) and lower thickness. The Diana-2's airfoil sections are even thinner then original SZD-56's, ranging from 12.8% at the root to 12.2% at the tip (and much less at the winglets). Even though the profiles are thinner than the original Diana's airfoils, the stiffness and strength characteristics are significantly better, and they maintain a higher cross-section area. This has a great impact on wing weight, structure, and the volume available for water ballast. Flaperons were used instead of separate flaps and ailerons. Figure 7 shows a comparison between new and old airfoil shapes, while Fig. 8 summarizes the expected aerodynamic characteristics. Expected drag reduction of about 20 to 25% over the entire range of lift coefficients is seen.

Aerodynamic design of the wing

As noted above, a new wing with entirely new aerodynamics has been designed. The fuselage and tail are the same as that of the old SZD-56 Diana. The proven inner wing structure is also retained (but design stresses in the monocoque skin were reduced by ~10%). The aerodynamic design of the wing includes three main stages[6]: planform design, airfoils design, and finally reduction of adverse interference effects (mainly in wing-fuselage intersection and wing-winglet juncture). The main objective of aerodynamic design itself is to achieve the best possible performance at various soaring situations, including a low stall speed and low sink rates at all speeds. Good stalling characteristics, effective ailerons, good flying qualities in thermals, and low sensitivity to bugs and rain are additional requirements.

At lower flying speeds, the wing drag is about 90% of total glider drag (about 65% is induced drag). At high speeds, wing drag is about 60% of total glider drag (the greater part of which is profile drag). Considering this, it is obvious that the main objective during the aerodynamic design process of a glider should be the reduction of both profile and induced drag. The first is possible by designing a wing with the maximum extent of laminar flow. Due to the fact that flow conditions (such as Reynolds number and lift coefficient) vary along the span, the airfoils should be designed specifically for each spanwise station in order to satisfy the actual requirements. Minimization of induced drag can be achieved by the proper distribution of load along the span by using the optimum planform and adding winglets.

The process of the Diana-2 wing design includes a number of considerations and must take their mutual interactions into consideration. To name just a few, there is improvement of high-speed characteristics (lowering contribution of parasitic drag), internal volume, and strength characteristics. Given these considerations, the Diana-2's wing area is slightly larger than the original Diana ($8.65m^2$ vs. $8.16m^2$).

A few computer programs have been used. They allowed for flow analysis, design and optimization of two-dimensional wing profiles,[7] as well as the entire three-dimensional glider configuration[8]. The wing planform is totally curved. This reduces both induced drag and wing profile drag, as well as allowing for the proper wing stall progression. The wing profile changes along the span. The optimum load distribution along the wing/winglet span was determined by applying Munk's induced-drag analyses. The optimum wing planform (more precise: local chord value) minimizing induced and profile drag is possible to evaluate by division of the above optimum load by optimum sectional lift coefficient. Modification to such a planform is undertaken in order to achieve proper stall progression along the span. All the design parameters, such as planform and profiles at various span stations, are subsequently updated to achieve the properties dictated by the iterative design process. The final planform and wing sections were obtained as a result of using three-dimensional optimization methods during detailed aerodynamic design. In the final stage, adverse interference effects between wing and fuselage,[9] as well as in concave corner of wing/winglet intersection, were removed.

The wing planform and the continuous family of wing sections used along wingspan are shown in Figs. 9 and 10 (expect for near wing-fuselage intersection sections). The entire internal volume of the Diana-2 wing is used as an integral water tank. The wings can carry 50% more ballast than previously, so the Diana-2 can fly at the highest as well as the lowest wing loading of any current 15-meter glider. When flying fully ballasted, nearly half the glider's weight is water ballast. The optimum balancing is achievable for any pilot weight through the 5.6-liter tail tank. The location of the center of gravity that minimizes trim drag is at 39% of mean aerodynamic chord.

The design of the glider and modified wings, including geometry definition, has been performed using *Unigraphics NX* system. The wing mock-up was made using CNC technology that enabled a precision of better than 0.1mm, which is crucial to benefit from subtle aerodynamic design.

The basic parameters of the new Diana are:

Wing span	14.942 m
Wing area	8.657 m^2
Empty mass	182 kg
Wing panel mass	46 kg
Water ballast (wings)	248 kg
Max. mass	500 kg
Min. wing loading	28 kg/m^2
Max. wing loading	58 kg/m^2

Sailplane performance analysis

The performance of Diana-2 was calculated using a rather unusual methodology. As performance of the old Diana had been measured and described in Mr. Richard Johnson's flight-test results, the evaluation of drag characteristics of the glider was possible. The wing drag characteristics obtained for the old Diana wing (calculated using a panel method with boundary layer interaction) allowed for the estimation of the drag characteristics of the remaining parts: fuselage, fin and tail. By adding the drag of the new wing, calculated using the same method, to these values, allows the drag characteristics of the new Diana to be estimated. It should be noted that the entire procedure was based on introducing numerical corrections of the wing characteristics to Johnson's flight-test results, which were used to predict the flight characteristics of the Diana-2. Experimental characteristics are not always smooth, so smoothing the parasitic drag characteristics was necessary. Flight tests had been completed for only one wing loading, so the same parasitic drag characteristics were used for other wing loadings. Weight changes were considered only in the numerical calculations of the wing characteristics. The prediction for maximum L/D (with water ballast) exceeds the almost mythical 50:1 boundary for racing class sailplanes. Final speed polars for the clean wing at different sailplane weights are presented on Fig. 11.

As the airfoils applied on new wing show considerable high sensitivity to the proper flap settings, a detailed analysis of flap position influence on the speed polars was of primary importance. Computational optimum of flap position for various sailplane weights and speeds are presented in Fig. 12.

Also of importance is the influence of insects/rain on the glider performance. An approximation of the roughness caused by bugs was achieved by specifying a much lower value of critical amplification factor N_{CR} used for analyzing laminar boundary layer stability and transition. In the presented computations N_{CR} = 5 was used. Flow conditions related to rain were approximated by specifying a very low value of $\boldsymbol{N_{CR}}$ and a forced transition at 7% of the chord on upper and lower surfaces. Results for sailplane mass of 350kg at various flow conditions and flap settings are presented in Fig. 13. The conclusion is that the approximation of bugs leads to only minor performance deterioration over a wide range of speeds. In fact, the only significant lost of efficiency is expected at high speeds. However, the optimum flap settings change significantly. Rainy conditions are expected to lead to much worse sailplane performance. On the other hand, the estimated loss is still much lower then for any other high performance glider. The other feature worth mentioning is the very low sensitivity of wet wing to flap setting.

Cross-country performance of the sailplane

The methodology described for thermal flight analysis was not only useful for selecting optimum design parameters for the sailplane, but also for coming up with some rules to help piloting decisions concerning the optimal ballasting of the glider in flight (depending on weather conditions, thermal strength, and size). The circling analysis was restricted to a maximum allowable lift coefficient of $C_L=1.4$, which is probably slightly conservative.

Two basic weather models were used. The first one included no cloud streets ($rl_{CS} = 0$, $r_{CS} = 0$) and interthermal descent has an intensity of 10% of the maximum thermal lift in the core ($r_d = 0.1$), which is equivalent to about 20% of the sailplane average climb rate. The second model was characterized by cloud streets reaching 20% of the total way between thermals with their mean lift of 30% of the thermal core value ($rl_{CS} = 0.2$, $r_{CS} = 0.3$). The intensity of the interthermal descent was the same as for the first model ($r_d = 0.1$).

Figure 14 shows the relationship between the sailplane mass and the expected average cross-country speed and net climb rate for the first weather model (no cloud streets), wide thermals and different thermal strengths (w_{T0} = 2.5 m/s & w_{T0} = 3.5 m/s). Similar results were obtained for both weather models, three thermals (wide, medium and narrow) and various thermal strengths W_{T0} (1.5 ÷ 7.0 m/s). A relatively strong influence of mass on climb rate is observed. Nevertheless, the distribution of the final average cross-country speed is very flat near optimum. The most significant benefit from either heavy ballast or a lighter sailplane - which correspond to either high or low allowable wing loadings - is expected mainly for very strong and very weak thermal conditions.

Figure 15 presents the optimum sailplane mass vs average climb rate relationships for both kinds of weather conditions and wide thermals. Additional boundaries of a 1% penalty on the average cross-country speed (thin line) and constant thermal strength conditions (broken oblique lines) are marked. Solid points represent the measured values extracted from flight logs (year 2005: Polish Open Class Nationals and European Championships). The average climb rate was defined as a sum of all the altitude gained in circling and the difference of altitudes at start and finish divided by the total time spent circling. The average cross-country speed includes the real kilometers flown (not the task distance only).

Analogical analysis has been performed for narrow and middle thermals. Examination of flight log results indicates that the wide thermal model is the most relevant; however, often lengths and strengths of cloud streets were greater then assumed in the calculations. Hence the real average cross-country speed is sometimes higher than predicted. Quite unusual and slightly surprising is the significant underestimation of calculated cross-country speed in strong thermal conditions (climb rate about 2.5 m/s).

Commonly applied for average cross-country performance analysis is the mixed weather model of Quast[2], which consists of some portions of wide and narrow thermals of strong and weak types. Obviously, the main objective of the analysis presented here is the determination of the amount of water ballast optimal for various thermal strengths. A family of mixed thermals – narrow and wide - with the same vertical velocity at 60m-radius position from core center, was specified. The same as in Quast's model, the assumption was made that 84% of the total flight distance is dominated by wide thermals, whereas 16% by narrow thermals. Mean value of the interthermal descent is 10% of the maximum vertical velocity inside thermal core, which means approximately 20% of average climb ratio. Figure 16 shows the relevant results.

It is worth noting that the mixed weather model similar to Quast's leads to a different optimum of sailplane's mass compared to the model including wide thermals only, but the expected average cross-country speeds in both cases are rather similar (the model including some amount of narrower thermals predicts a few km/h lower speed). Comparison of the presented computational results to those extracted from flight log data suggests some overestimation of the narrow thermal presence in Quast's model.

The most important conclusions from the analyses concerns the optimal amount of water ballast for various average climb rates. Generally, the optimum is higher then the values usually presented in literature. A maximum sailplane mass of 500 kg is expected to be optimum for average climb rate above 1.75 m/s in the case of wide thermals and no cloud streets. In the case of cloud streets of 20% relative length and 30% strength, the maximum sailplane mass should be used at climb rates above 1.5 m/s. The minimum practical achievable mass of about 280 kg (in the case of 80 kg pilot + equipment) achieves an optimum for 1 m/s and 0.9 m/s respectively. Expectation is that removing of 50kg water ballast should improve the average climb rate by about 0.15 m/s. The values of masses should be slightly lower in the presence of some fraction of narrow thermals. It is interesting that the mixed model affects mainly high mass characteristics with little influence on the light sailplane. On the other hand, the dependency between mass and final cross-country speed is very flat near the optimum. Over- or under-ballasting the sailplane by 50 to 70 kg (about +/- 15% of the sailplane optimum mass) leads to the loss of about 1% of the average speed.

Conclusions

The design process of a modern high-performance sailplane is rather demanding issue. A high level of sailplane aerodynamics has been achieved through the use of advanced computational design tools and extensive wind-tunnel investigations. Any further significant improvements in sailplane flight performance through drag reduction (especially profile drag) is almost impossible without the use of new flow technologies (e.g. active flow control of boundary layer). Some moderate improvement of overall sailplane performance can still be achieved by careful aerodynamic design of every detail of the sailplane and new solutions for sailplane structure and technology. A relatively broad scale of possible improvement in final flight performance is still possible in the area of low-speed characteristics (climb performance). Apart from proper design choices, wide and detailed final performance analysis, including off-design conditions, must be performed because of pilots' requirements.

References

[1]Horstmann, K.H., Neue „Modellaufwindverteilungen und ihr Einfluss auf die Auslegung von Segelflugzeugen" OSTIV Publication XIV, 1976

[2]Thomas, F., *Fundamentals of Sailplane Design*, College Park Press, 1999

[3]Cochrane J.H., "MacCready Theory with Uncertain Lift and Limited Altitude", *Technical Soaring* 23(3) (July 1999), also: http://www.gsb.uchicago.edu/fac/john.cochrane/research/Soaring

[4]Almgren, R., Tourin, A., "The Mathematics of Gliding Racing," RCA, Nov. 7, 2004 (http://www.math.toronto.edu/almgren/optsoar/)

[5]Boermans L.M.M, van Garrel A., "Design and Windtunnel Test Results of a Flapped Laminar Flow Airfoil for High-Performance Sailplane Applications" – ICAS 94-5.4.3

[6]Kubrynski K., "Wing-Winglet Design Methodology for Low Speed Applications", AIAA Pap. 03-0215, 41 Aerospace Science Meeting, Reno, 2003

[7]Drela M., "XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils", in *Low Reynolds Number Aerodynamics*, Ed. T. J. Mueller, Lecture Notes in Eng. 54 (1989)

[8]Kubrynski K., "Subsonic Aerodynamic Design Via Optimization", Ed. K.Fuji, G.S.Dulikravich, *Notes on Numerical Fluid Mechanics*, Vol. 68, 1999, Vieweg

[9]Boermans L.M.M, Kubrynski K., Nicolosi F., "Wing-Fuselage Design of High-Performance Sailplanes" – *Boundary Layer Separation in Aircraft Aerodynamics*, ed. Henkes R.A.W.M., Bakker P.G. – Delft 1997

[10]Johnson, R.H., "A Flight Test Evaluation Of The SZD-56-1 Diana Sailplane" - *Soaring*-April 1999

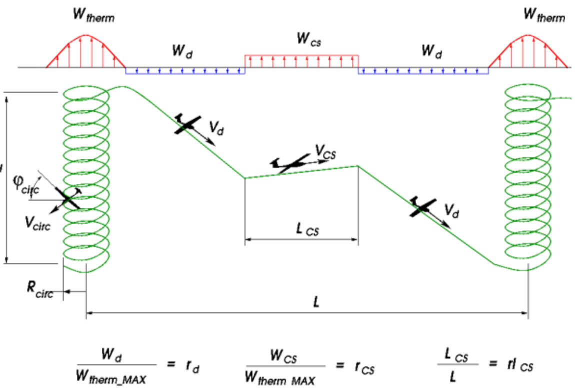


Figure 1 Assumed cross-country flight pattern.

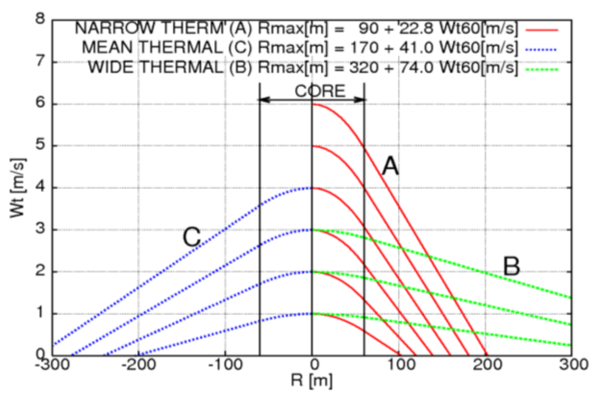


Figure 2 Assumed lift distribution in model thermals.

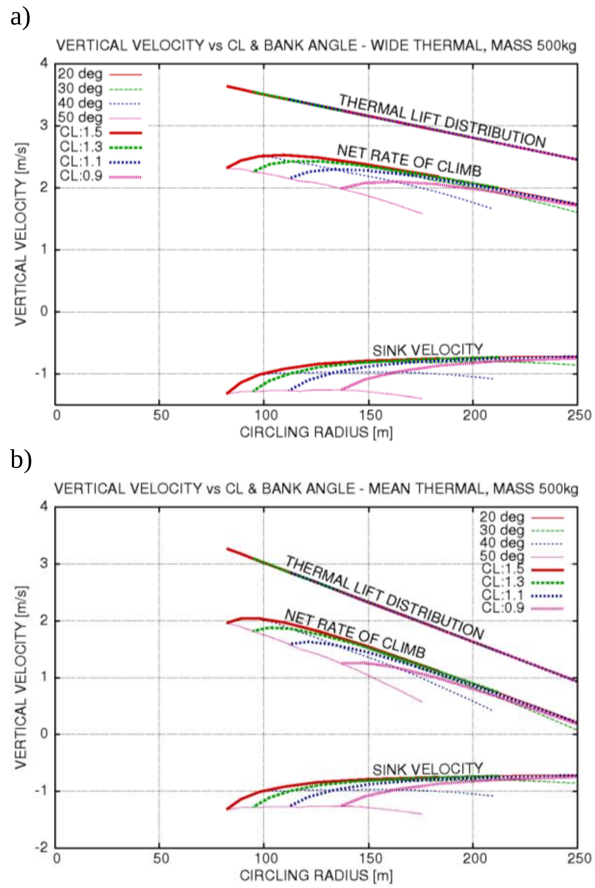


Figure 3 Influence of lift coefficient, circling radius and bank angle on climb performance: a) wide thermal (B), b) middle thermal (C).

a)

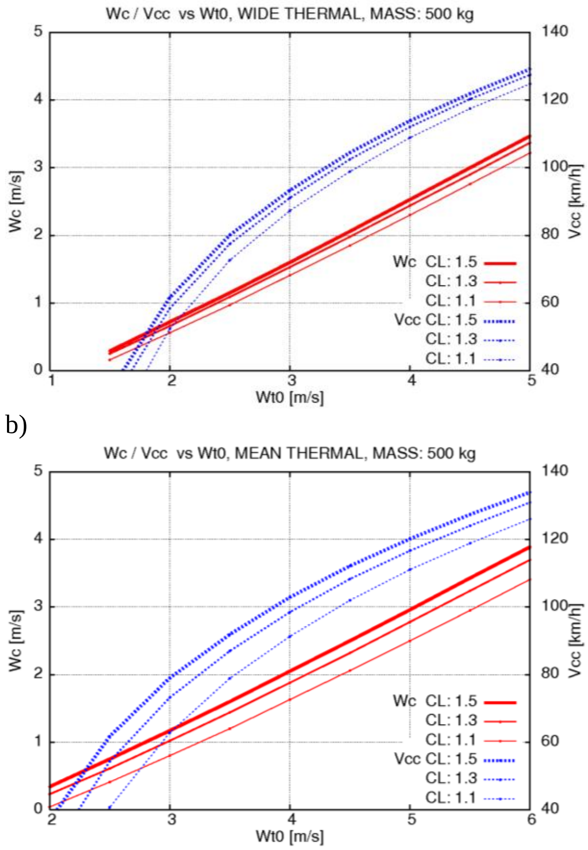


Figure 4 Influence of lift coefficient and thermal strength on climb rate and average cross-country speed (no cloud streets): a) wide thermal (B), b) middle thermal (C).

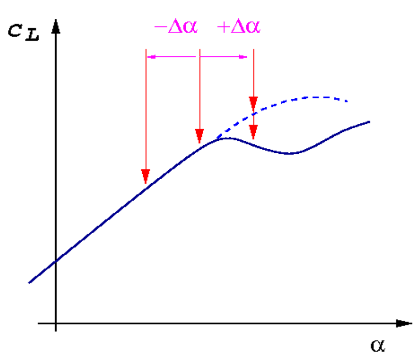


Figure 5 Sketch of airfoil behavior at angle of attack changes due to vertical gust.

a)

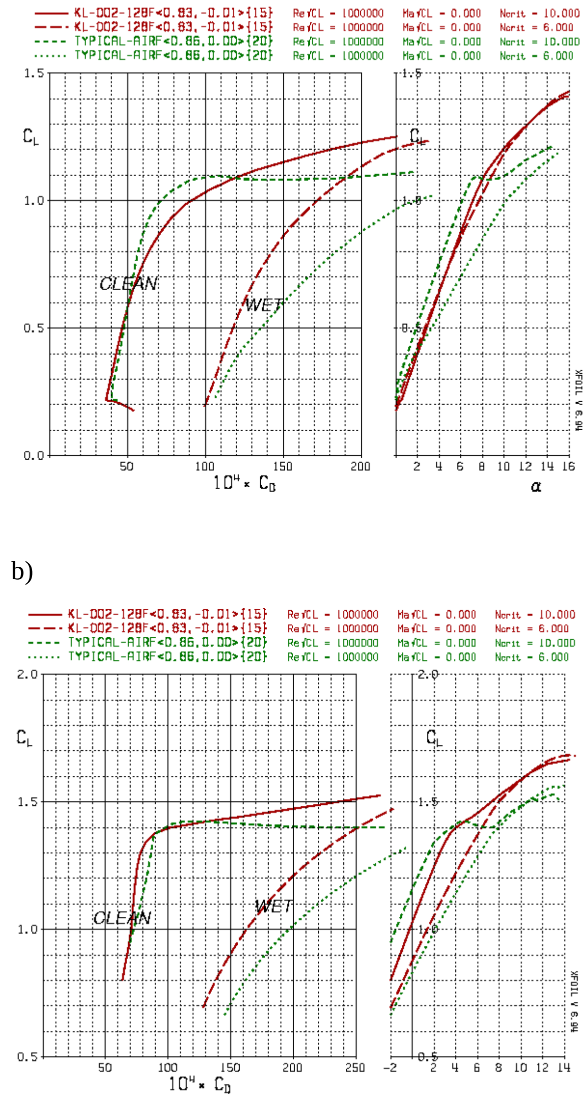


Figure 6 Computational characteristics of Diana-2 airfoil and typical modern airfoil – clean and wet conditions simulated, a) no flaps, b) flaps down.

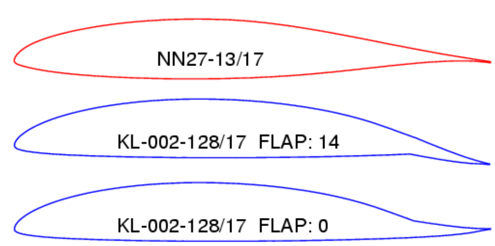


Figure 7 Old and new of Diana wing airfoils.

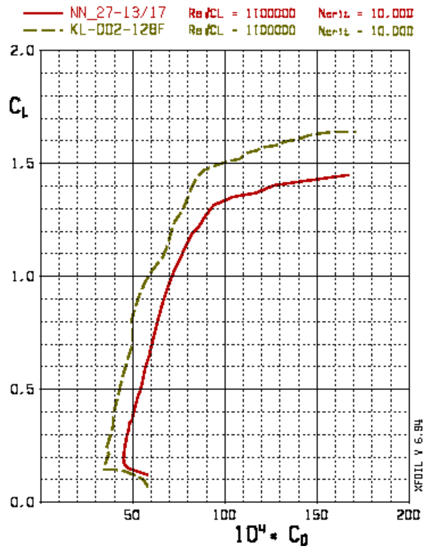


Figure 8 Drag polars of new and old Diana airfoils.

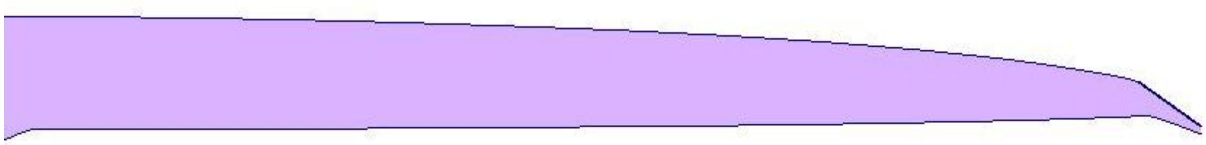
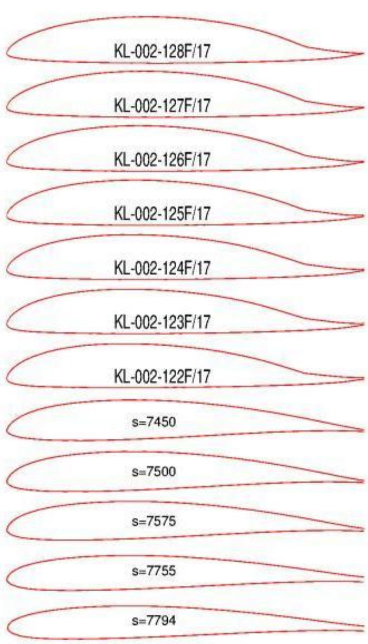


Figure 9 Wing planform (developed surface).



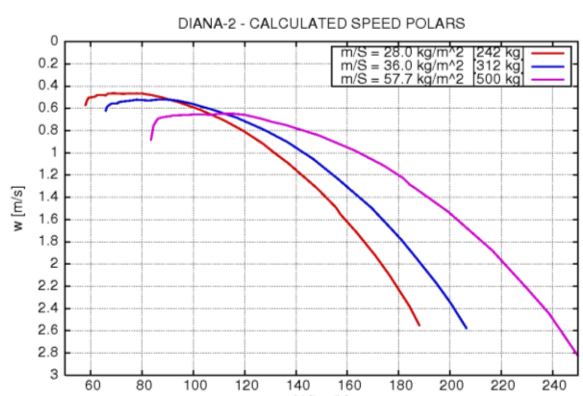


Figure 11 Diana-2 calculated speed polars.

Figure 10 Geometry of the wing and winglet airfoils.

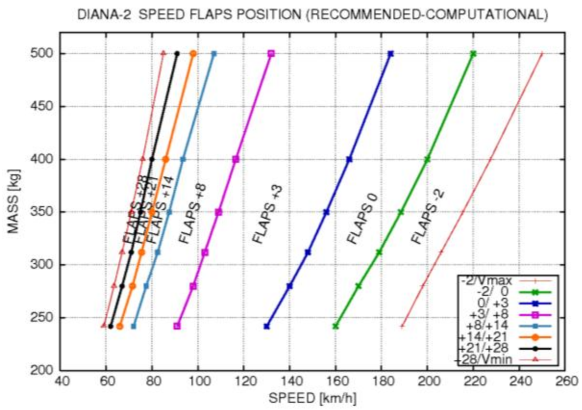


Figure 12 Calculated optimum flap settings.

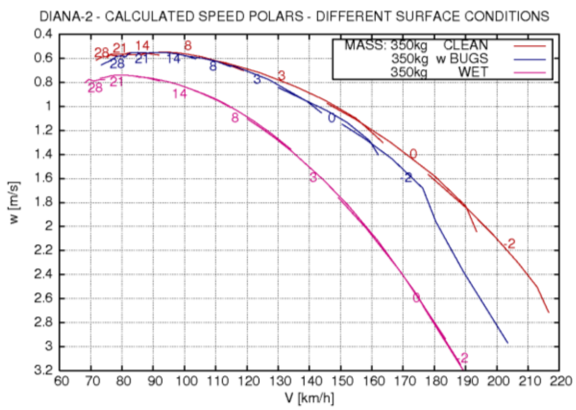


Figure 13 Simulation of clean wing, bugs and rain in performance calculations (mass: 350 kg).

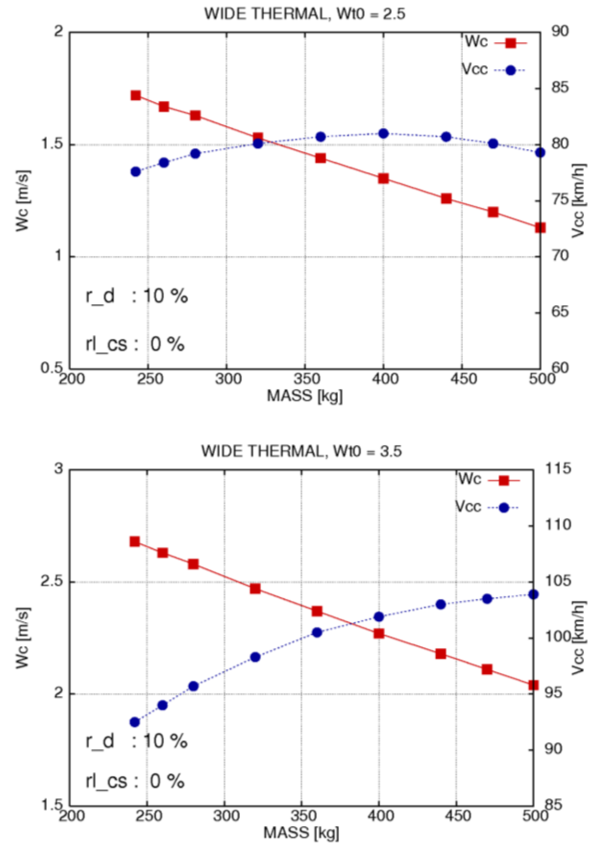


Figure 14 Sample computational cross-country flight characteristics of Diana-2 at two thermal strengths.

a)

b)

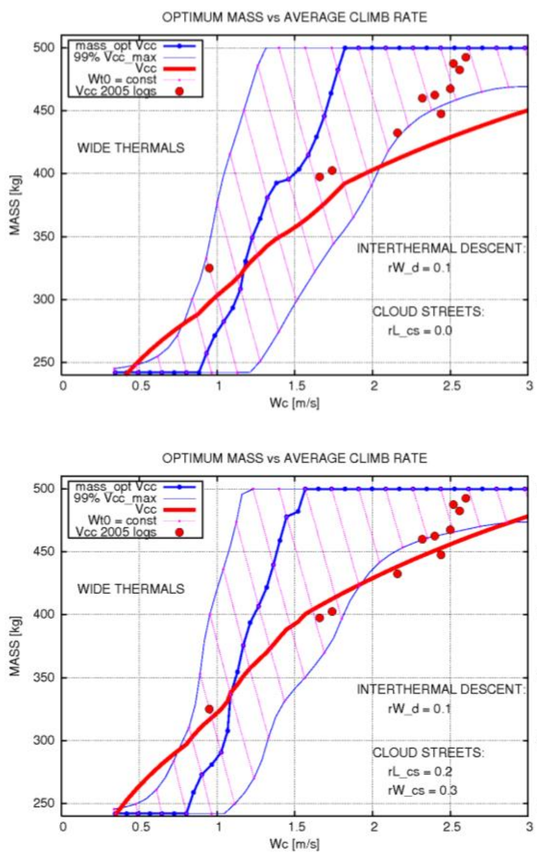


Figure 15 Optimum Diana-2 mass vs. climb rate for wide thermals and two weather models: a) no cloud streets, b) with cloud streets.

a)

b)

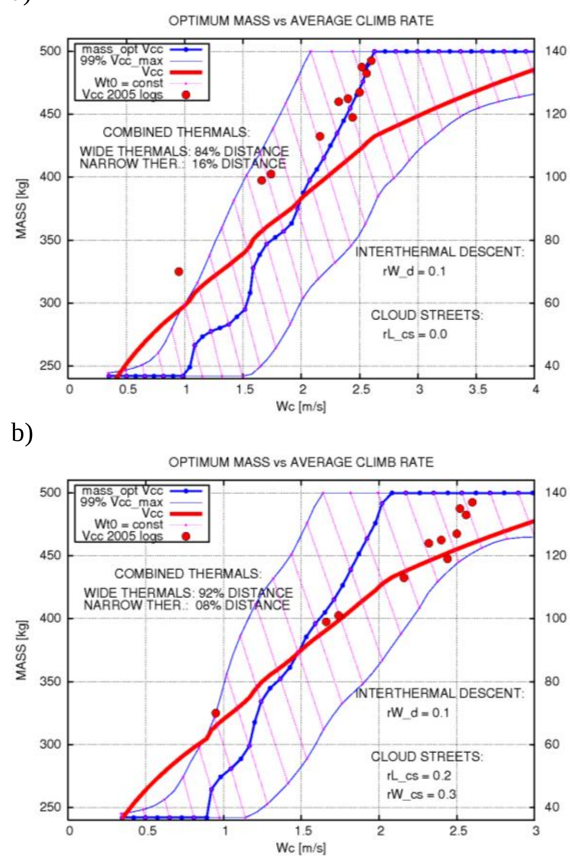


Figure 16 Optimum sailplane mass and expected cross-country speed for mixed thermals and two weather models a) no cloud streets, b) with cloud streets