The "Flight Template"

A tool for the optimization of sailplane aerodynamic for cross country flight at preliminary design stage

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Abstract

A new tool for sailplane wing aerodynamic optimization is proposed, in order to take the specificity of a typical cross country flight into account in the optimization process at preliminary design stage. It is called "Flight Template", because it embodies the statistical aspect of real flight. This "Flight Spectrum" acts as a filter of aerodynamic wing characteristics, and helps defining relevant cost function reflecting global performance for multiple-point optimization. In a first part, the concept of Flight Template is presented, and a methodology is proposed to determine it experimentally. Some documented examples are given. In a second part, applications of the Flight Template tools in preliminary design process are presented. Illustration of the use of Flight Template are given for airfoil selection, plan-form optimization and airfoil numerical optimization

Nomenclature

C_L	=	lift coefficient
C_D	=	drag coefficient
AR	=	Aspect ratio
ϕ	=	bank angle
$\dot{\Psi}$	=	heading scrolling in turn

Introduction

Sailplane wing numerical optimization is a real challenge to put in equation and figures. Contrary to airliners, that are designed for one single cruise condition, sailplanes are flown over a very large range of speed and lift coefficient conditions. Relevant performance figure is more difficult to define for sailplanes.
When applying single point classical process, for one lift coefficient condition C_L, optimization leads to radical design, not adapted over a wide speed range.
The goal of the "Flight Template" defined here is to define an aerodynamic optimization process representative for the condition actually encountered on sailplane during a cross country flight.
It will provide a weighting of performance as function of C_L, that can be used very simply.

PART 1 : Flight Template Concept

Theoretical background

For gliding, a sailplane extracts power from gravity. It is brought back to the ground due to the work of drag. Considering this, we shall search the design that minimizes power absorbed by drag over the whole flight duration. This will be the starting point for defining a cost function.

Elementary work *dE* absorbed by drag *D* during a short period of time *dt* can be written as :

$$dE = D \times V dt = 1/2 \rho S V^3 C_D dt$$

The normalized mean power $\overline{P}$ absorbed by drag force during a flight period T is proportional to the sum of those elementary work over the flight, as follows :

$$\overline{P} = \frac{\int dE}{T} = \frac{\rho S}{2T} \int_{\text{Flight}} C_D(t) V^3(t) dt \quad \textbf{Eq 1.}$$

By mathematical operation (see Appendix), the sum performed over the flight duration can be transformed into a sum over C_L range :

$$\overline{P} = \frac{\rho S}{2}\int_{C_L \text{ range}} C_D(C_L)V^3(C_L)\, f_t(C_L)dC_L \text{, with}$$

$$\boxed{f_t(C_L) = \frac{1}{T}\frac{d\tilde{t}}{dC_L}(C_L)} \quad \textbf{Eq 2.}$$

A function $f_t(C_L)$ is defined (Eq 2) , and is called the “Flight template”. It corresponds to the C_L spectrum over the flight : for one given C_L, the value of $f_t(C_L)$ represents the density of time spent at this C_L condition.

What we need for building this function is a discrete recording of C_L history over the flight.

NB : Flight Template must be “normalized”. At the end of the process, we should have :

$$\int_{C_L range} f_t(C_L)dC_L = 1$$

Definition of an aerodynamic cost function

If the flight is quasi steady, that is “little maneuver are performed”, C_L and speed V are correlated through the following relation :

$$V = \sqrt{Nz}\,\frac{V_1}{\sqrt{C_L}} \quad \textbf{Eq 4.}$$

Where V_1 and Nz are computed from :

$$V_1\left(\frac{m}{S}, h\right) = \sqrt{\frac{2g}{\rho(h)}\frac{m}{S}} \quad \textbf{Eq 5.}$$

$$Nz = \frac{1}{\cos\phi} = \sqrt{1-\left(\frac{V\dot{\Psi}}{g}\right)^2} \quad \textbf{Eq 6.}$$

V_1 is a function of wing loading and pressure altitude, and Nz is computed from the path. Here ϕ is bank angle, and $\dot{\Psi}$ is heading scrolling in turn.

This case corresponds to classical “calm” flight of a sailplane and thermaling.

The mean power $\overline{P}$ absorbed by drag force during the flight period is then expressed by :

$$\overline{P} = \frac{\rho S V_1^3}{2} \times \overline{\left(\frac{C_D}{C_L^{3/2}}\right)}$$

It means that a driving parameter from aerodynamic point of view, weighted by the C_L history is the following product :

$$\overline{\left(\frac{C_D}{C_L^{3/2}}\right)} = \int_{C_L \text{ range}} \frac{C_D(C_L)}{C_L^{3/2}}\, f_t(C_L)dC_L \quad \textbf{Eq 7.}$$

Here the “Flight template” implicitly translates drag time history during a flight in term of weighted aerodynamic coefficient.

This quantity must be minimized, and is a very simple and interesting cost function within a numerical optimization loop.

Determination of flight templates from GPS recording

For defining a relevant cost function, Flight Template must be representative of real flights. A strategy of determination, from GPS recording, was developed and applied.

GPS device is widely used for navigation and flight recording in the gliding community. A large flight recording database is easily available on the Internet (see www2.onlinecontest.org for instance). Knowing the weight of the glider, V_1 can be computed (see Eq. 5), and the path can be post-treated to obtain the C_L history of the flight (from Eq 4.). From this C_L history, the C_L spectrum of the recording can be determined.

IGC file are quite raw information coming out of the GPS, post-treatment is to be performed to get C_L history from flight path. The following operation must be implemented :

- Filter position signal and ground velocity vector **V**
- Evaluate mean wind vector **W**
- Evaluate load factor Nz using Eq. 6
- Then compute C_L using Eq. 4

Such a program was written, and many flight paths were processed, in order to create a Flight Template data bank.

Selected examples of flight templates

From each flight recording, a specific Flight Template can be produced. The detail of one Flight Template is dependent on the specific pilot, meteorological condition etc…

Here are presented some specific examples that were studied.

Three flight displayed here were all performed from French gliding center, CNVV in St Auban. The pilot was Denis Guerin, glider was a Ventus 2a (contest number : EQ). All three flights were performed over the same region, which is mountainous area. On a

typical day in this region, strong thermals and ridge lines allow little circling time.
Three successive days were recorded. Wing loadings were different : respectively 34, 40 and 47 kg/m² for 1rst, 2nd and 3d flight.

Airspeed spectrum analysis
The airspeed spectrum represents the time spent at each speed of the speed polar. On fig 1 it is shown that all three flights were performed over a rather large speed range.

- First flight was the shortest test flight in term of covered distance. It was performed at the lightest wing loading on a poor day and is also the slowest (airspeed range rather in left corner).
- Second flight was performed with heavier wing loading. Two speeds are noticeable, corresponding to circling (105km/h) and straight flight (155km/h).
- Third flight corresponds to the maximum distance covered. He was performed at wing loading close to maximum, on a very good weather for gliding. Mean speed is the fastest, with little circling time (reduced low speed peak).

Flight Template analysis
In term of "C_L spectrum" the situation is quite different from the airspeed spectrum. Flight Templates resulting from those three flights are shown on Fig 2.
It can be observed that for the three flights presented here, which were quite different flights, Flight templates are quite close at the end. They all three present a peak around C_L=0.4~0.5, meaning this lift coefficient is the most used during flight.
The transcription from speed to C_L takes into account the wing loading. Wing loadings were really different for the three presented flights, that is why speed spectrum differ so much, and not C_L's.

Comment
It seems that the pilot uses the sailplane, from an aerodynamic point of view (i.e. lift coefficient), always in a similar way.
From a handling point of view, this corresponds to using the same flap setting and pitch attitude, whatever the wing loading. This would mean a trained pilot seems to drive the glider to reach given aerodynamic conditions on the wing.
This conclusion can be generalized to a very wide number of cross country flights.

Envelope Flight Template strategy

It was shown that each flight produces a specific Flight Template. However, while studying a large set of GPS recordings, it was found that Flight Templates have always similar characteristics.

For preliminary design use, it is interesting to have one single reference flight template. Flight for various glider pilots, wing loadings and weather conditions were considered.
An "Envelope Flight Template" was derived from current experience dealing with flight post processing (See fig 3 and Table 1).

The envelope obtained represents a statistically relevant aerodynamic history of a cross-country flight for current sailplane in Europe.

This Envelope Flight Template is a very interesting tool for sailplane preliminary design, and is very easy to use.

Example of the use of this Envelope Flight Template will now be detailed.

PART 2 : Using Flight Templates

In parallel to this theory, simple but accurate computations tools were developed in order to evaluate the feasibility of optimization scheme as proposed. Documented examples are now detailed.

Envelope Flight Template used as "Polar filter"

Drag polar is a key point for airfoil selection. Airfoils can be compared according to different criteria, as for instance their minimum drag C_{Dmin} , maximum lift C_{Lmax}. For a sailplane, the whole evolution of C_D versus C_L is to be considered (see ref 1).

Here are presented some results of Xfoil calculation (see ref 2) for five existing sailplane airfoils, with number of Reynolds varying along polar ($Re*Sqrt(C_L)=1.250\ 10^6$). Airfoil coordinates used for this study were either public or evaluated from photo (with no guarantee in accuracy).
Flight Template is used as a multiplying filter on $C_D/C_L^{3/2}$ as a function of C_L. This creates the function to be summed for computing $\overline{\left(\frac{C_D}{C_L^{3/2}}\right)}$ (ref. to Eq 7.)
This manipulation highlights certain part of the polar. It helps finding where the differences between the airfoils affect the most the performance from an operational point of view.
From fig 5 we may observe that $C_D/C_L^{3/2}$ curves differs for high C_L values, and are difficult to compare at C_L~0.4. When weighting using the envelope Flight Template (fig 6.) high C_L region is somewhat flattened, whereas C_L~0.4 region is magnified. This gives details on the differences that influence the most global airfoil performance.

Summing this weighted $C_D/C_L^{3/2}$ with respect to C_L gives $\overline{\left(\frac{C_D}{C_L^{3/2}}\right)}$ (cf. **Eq 7.**). This figure is directly proportional to the power absorbed by the airfoil drag during a typical cross country flight performed according to the Envelope Flight Template program.
Results for the tested airfoils are presented below :

Airfoil	$\overline{\left(\frac{C_D}{C_L^{3/2}}\right)}$
HQ-300GD-mod2 (public coord.)	0.01640365
FX S 02-196 (public coord.)	0.01731888
OAP1 (coord. from photo)	0.01620513
Eppler E603 (public coord.)	0.01638561
Discus (coord. from photo)	0.01467457

According to the criterion developed in this paper, Discus airfoil is the best suited airfoil for minimizing the power absorbed by airfoil drag during a typical cross country flight. The relatively low C_{Lmax} level, compared to the other airfoils, does not appear to affect the overall performance determined by the current weighting.

NB : the weighting defined here highlights the ability to minimize power absorbed by drag, and not ability to climb (note that Discus glider, which seems to be the favorite in this theory, is not a good climber). That is probably why high C_L region is so less weighted.

Envelope Flight Template for Plan-form Optimization

AR selection is also a key factor in sailplane design. For standard & 15m class, the AR is to be optimized with fixed span. This is a multidisciplinary topic (Aerodynamic & mass), and Flight Template gives a relevant insight into aerodynamics aspect.

Calculations were performed on different wings for a given airspeed (V=35m/s). Baseline plan-form was Discus wing, and homothetic transformation was applied for AR variation at given span (fig 7).
An extended lifting line (ref 3) was used in order to compute both induced and airfoil drag for those geometries (fig 8). This computation method is refined enough for capturing fine Reynolds effect along the wing. It is also quick enough for computing many configurations within a short period of time.
Drag split on Fig. 9 shows an expected result : it is known (ref (1)) that increasing AR enables to decrease CD_i at given C_L, whereas it increases $CD_{airfoil}$ (considering fixed span b=15m).
Using the Flight Template as a filter, a relevant cost function is easy to compute, for sorting geometries.

The trend seems to show there is an aerodynamic optimum at around AR=30 (also, the optimum is reach by less than 1% for AR=27.5). This is an optimum in term of minimum power absorbed by drag during a cross country flight.
AR=30 is quite a high value for Standard class sailplanes : in standard class there would be room for aerodynamic progress with greater AR. It is likely that others constraints (e.g. mass aspect for given stiffness, ability to climb) restraints this optimum for standard class.
On the other hand, AR=27 corresponds to a common value in 15m class.

Envelope Flight Template for Airfoil Numerical Optimization

Flight Template can also be used within automated conception loops. An optimization program was written, for optimizing three airfoils parameters at the same time. The objective of this program is to minimize the cost function defined using Flight Template (see fig 11.)
This was mainly a primary attempt to optimization, in order to evaluate the feasibility of such a process.

Once again Discus airfoil was chosen as a reference airfoil. Degrees of freedom to be optimized were simple and physical : the airfoil was warped through the definition of maximum camber, position of maximum camber, and position of maximum thickness. Relative thickness of the airfoil was considered as a constraint.
Other degrees of freedom defining the airfoils may be defined (see ref. 4), and would provide a more refined optimization process.

For creating a new geometry, the original airfoil was perturbed, and an unconstraint optimization process was performed. The objective was to minimize $\overline{\left(\frac{C_D}{C_L^{3/2}}\right)}$. The optimization algorithm has used both global and local optimization method for converging up to the minimum of the objective function. It was necessary to perform 40 iterations for satisfying reasonable convergence criteria, accounting for 90 evaluations of the objective function.
As a result of the optimization the cost function was reduced by 1%.

The geometry created by the optimizer is plotted on fig 12, and compared with the original. Main characteristics of the airfoils are given bellow :

	Original Airfoil	Modified Airfoil
Relative thickness	15.80%	15.80%
Position of maximum thickness	41.00%	33.60%
Relative camber	3.71%	3.29%
Position of maximum camber	45.30%	43.80%
$\overline{\left(\frac{C_D}{C_L^{3/2}}\right)}$	0.01467457	0.01452589

The polar of the resulting airfoil is displayed on fig 13 as compared to the original,
The modified airfoil has a less pronounced drag bucket. There is a loss at the lower and upper end of the drag bucket for the original airfoil, compared to original airfoil.
Drag rise for the new airfoil also occurs for a higher C_L than for the original. This gain for the high C_L values compensates the loss of laminarity for lower C_L when considering the cost function as a relevant measurement for performance.
When detailing the weighted $C_D/C_L^{3/2}$ curves (fig 14) we observe an exchange of performance between high C_L and low C_L region. This exchange seems beneficial for the Flight Template used for evaluating performance.

As a result from the optimization, there was a gain on the Discus airfoil, which was already the most optimized among airfoils considered. The interesting point is also that the optimized airfoil has a geometry and a drag polar really different from the original airfoil. This means that these two different airfoils concepts provide a competitive efficiency during a cross country flight.

NB : for a given $\overline{\left(\frac{C_D}{C_L^{3/2}}\right)}$, airfoil selection can be performed on other parameters.
For instance, pitching moment for the modified airfoil is reduced by 12%, which can be of interest for optimization under pitching moment constraint (trimming drag modeling). The C_{Lmax} can also be an important matter, since it is to be linked to the ability to climb.

Conclusion

The so called "Flight Template" concept, developed in this paper, is a promising tool for sailplane preliminary design.
It is of very simple use as a filter of aerodynamic characteristics. It helps sorting aerodynamics design, by taking into account the specificity of a cross - country flight by the definition of a global performance cost function.
Its use within numerical optimization scheme has been evaluated, and is even more promising. The aerodynamic performance can be optimized in itself, as initiated in this paper for an airfoil. An integration of the aerodynamic performance within a Multi-Disciplinary Optimization process is now easy to imagine. The definition of the global cost function enables an easy integration of aerodynamic performance within a set of constraint from different disciplines.

Acknowledgments

I want to thank all the readers who take time for considering my writings. They were involved at different stage of the elaboration of this theory, from the primary idea to this OSTIV paper writing. Special thanks to Jean-Luc, François, Stephan and Jean-Paul, for their help.

Thanks a lot to Denis Guerin, who provide me with his flights during championships, and great deal of information about them.

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Appendix :
Mathematical handling for getting Flight Template from discrete C_L history

In eq 1, mean power absorbed by drag is basically expressed as a sum over the duration of the flight.

$$\overline{P} = \frac{\int dE}{T} = \frac{\rho S}{2T} \int_{\text{Real flight}} C_D(t) V^3(t) dt$$

At first, it is necessary to re-order the flight samples : we shall sort them according to increasing C_L. This manipulation does not change the value of the mean power, which is still equal to :

$$\overline{P_{\text{Real flight}}} = \overline{P_{\text{Re-ordered flight}}}$$

$$= \frac{\rho S}{2T} \int_{\text{Re-ordered flight}} C_D(\tilde{t}) V^3(\tilde{t}) d\tilde{t}$$

Then a single value of re-ordered time sample corresponds to a single value of CL, and vise versa.

$$C_L = g(\tilde{t}) \Leftrightarrow \tilde{t} = g^{-1}(C_L)$$

This was not the case in the initial, unordered, real flight recording

Now we can perform the change in variable within the sum, that is we consider C_D as a function of C_L history instead of time history. We have to do the following manipulation for evaluating the mean power $\overline{P}$:

$$\frac{1}{T} d\tilde{t} = \frac{1}{T} \frac{d\tilde{t}}{dC_L}(C_L) dC_L = f_t(C_L) dC_L$$

Then appears the "Fight Template" *ft(C$_L$)*. This function accounts for the normalized time $\frac{d\tilde{t}}{T}$ spent by the sailplane during the flight at a C_L contained within C_L range [C_L-dC_L/2 , C_L+ dC_L/2].

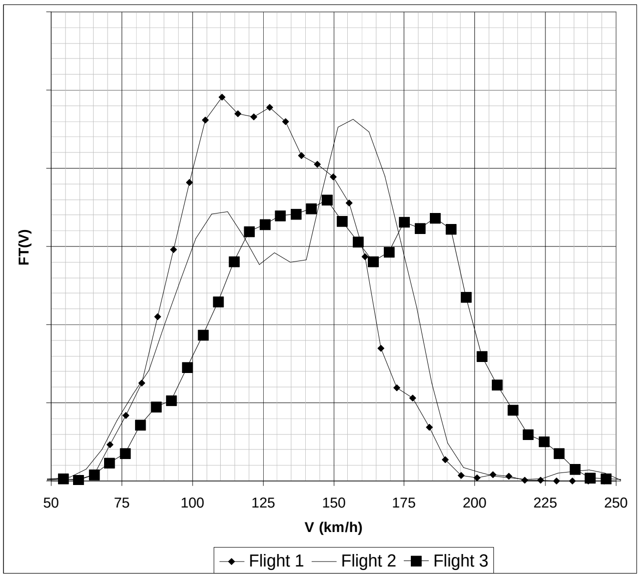

Figure 1 : Speed spectrum for the three detailed flights.

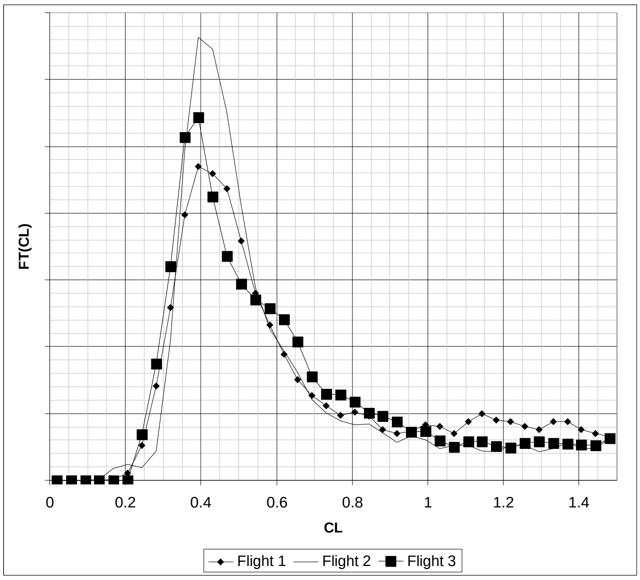

Figure 2 : Flight templates for the three detailed flights.

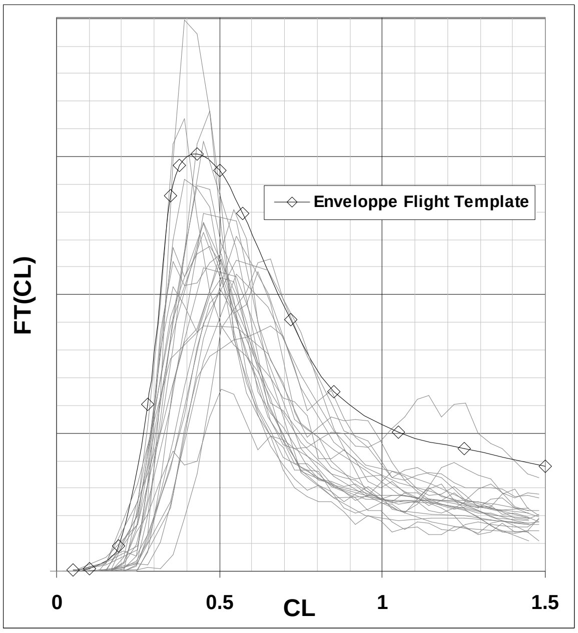

Figure 3 : Envelope flight template

CL	Flight template
0.05	0.003
0.1	0.005
0.19	0.045
0.28	0.302
0.35	0.680
0.375	0.735
0.43	0.758
0.5	0.727
0.57	0.649
0.72	0.455
0.85	0.325
1.05	0.253
1.25	0.222
1.5	0.190

Table 1 :

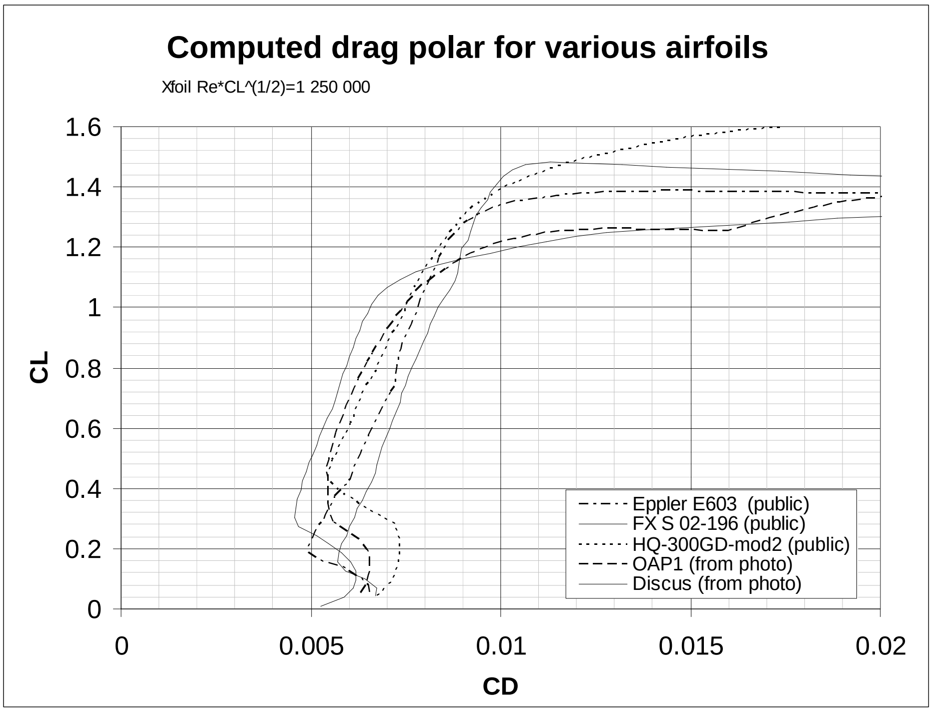

Figure 4 : Calculated drag polars for five samples airfoils

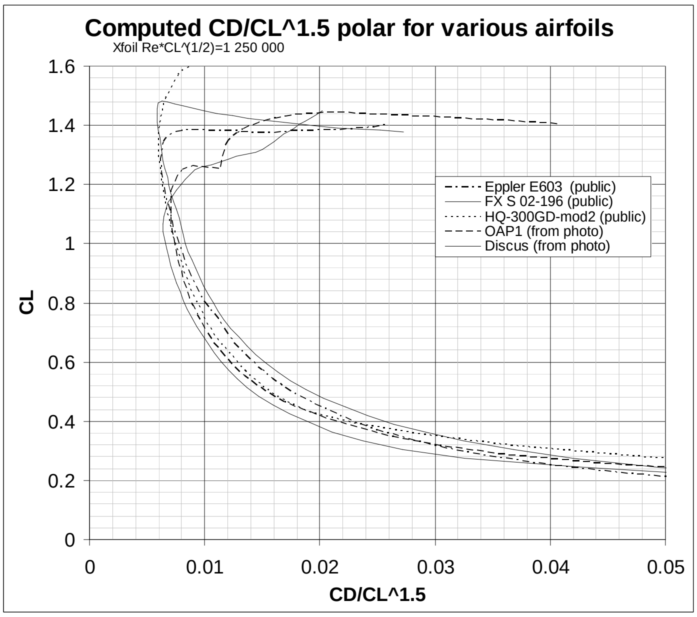

Figure 5 : Calculated CD/CL^1.5 polars for the same five samples airfoils

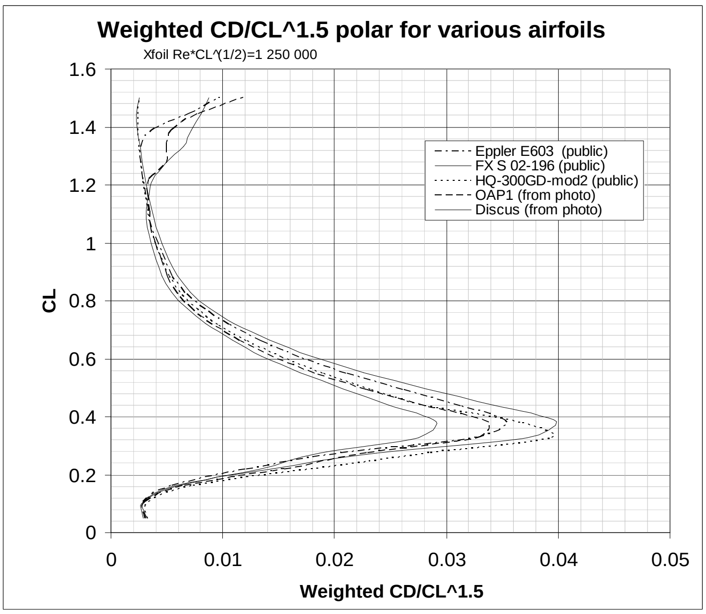

Figure 6 : Weighted CD/CL^1.5 polars for the same five samples airfoils

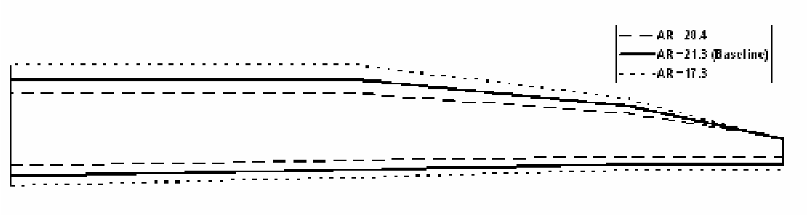

Figure 7 : Discus wing plan-form, and homothetic versions.

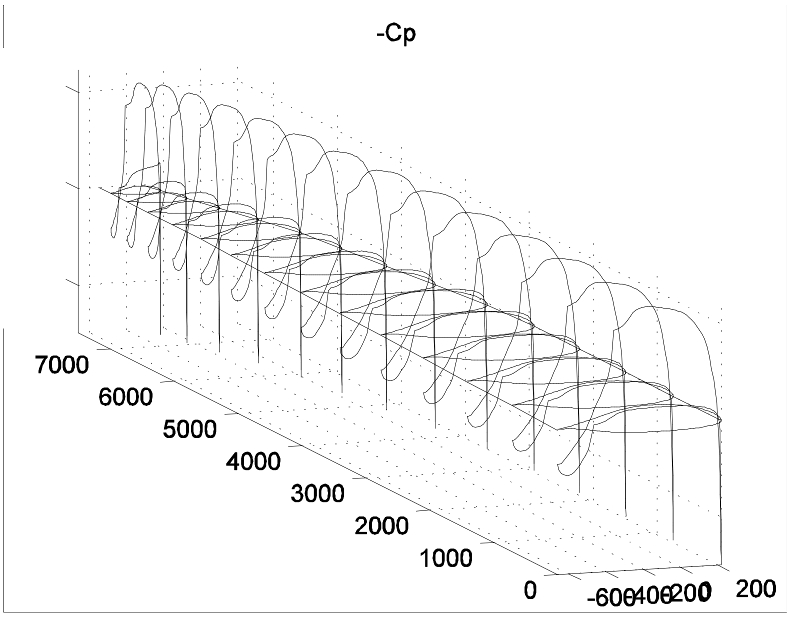

Figure 8 : The extended Lifting line theory computes local behavior of each airfoil, and induced drag.

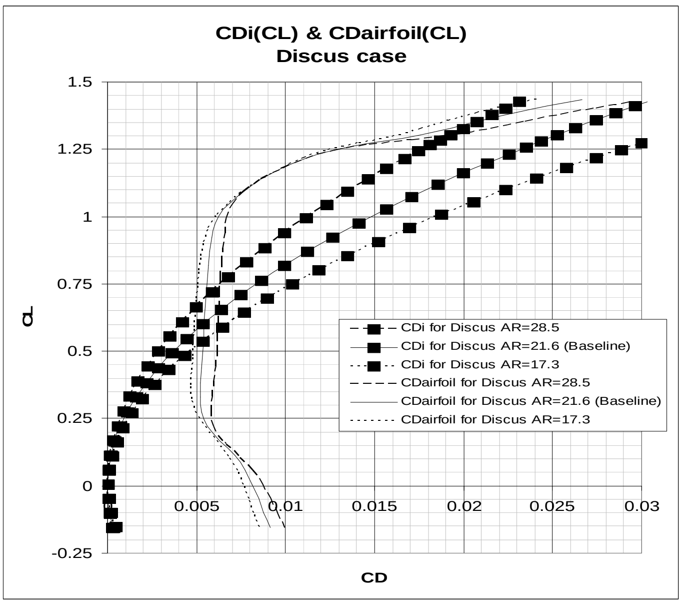

Figure 9 : Wing drag split, for various plan-form.

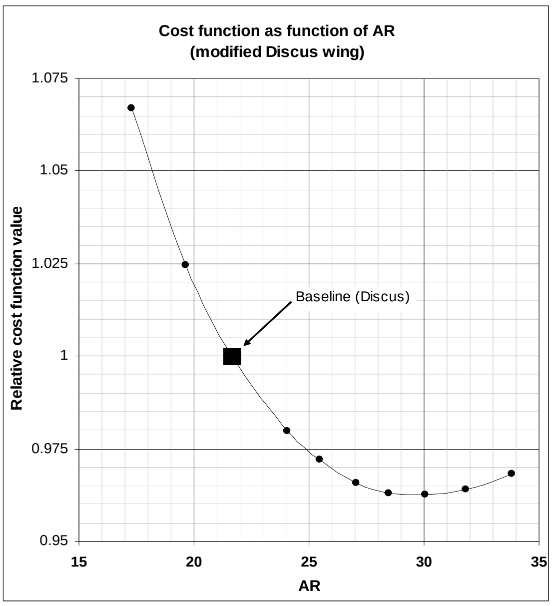

Figure 10 : Aerodynamic AR optimum, according to criteria derived from Flight template.

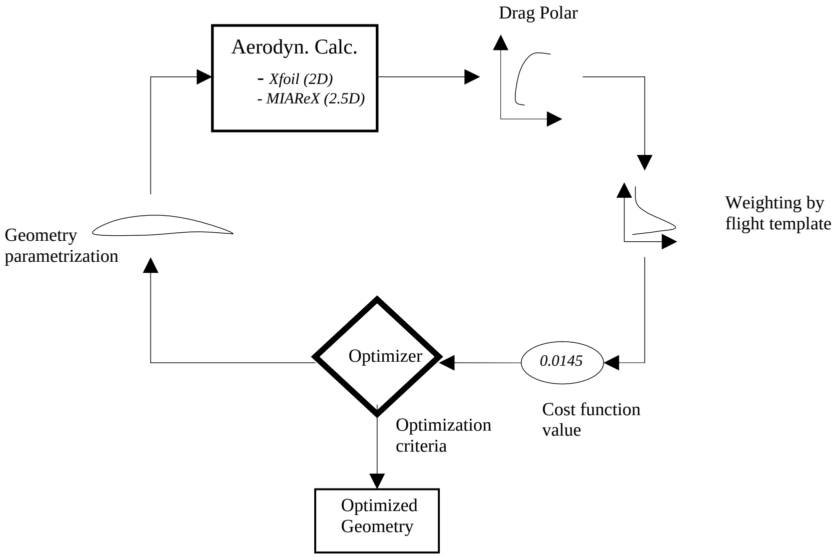

Figure 11 : Numerical optimization process scheme.

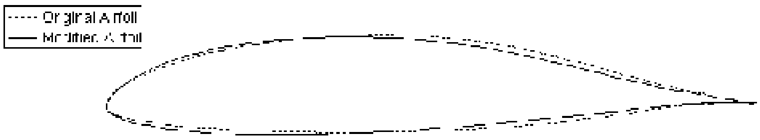

Figure 12 : Airfoil geometry resulting
from numerical optimization.

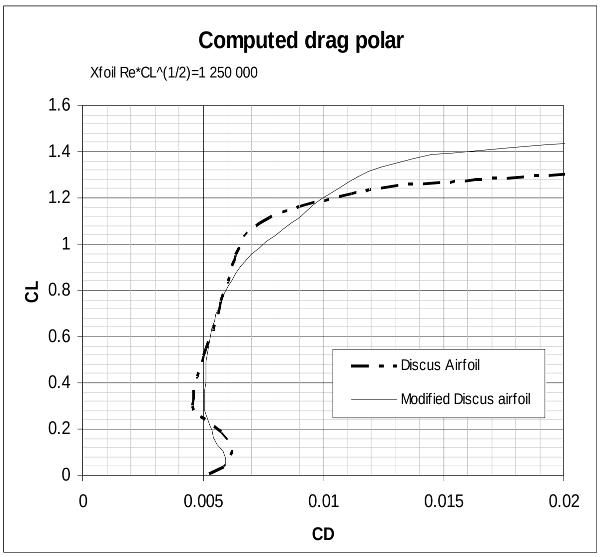

Figure 13 : Drag polars.

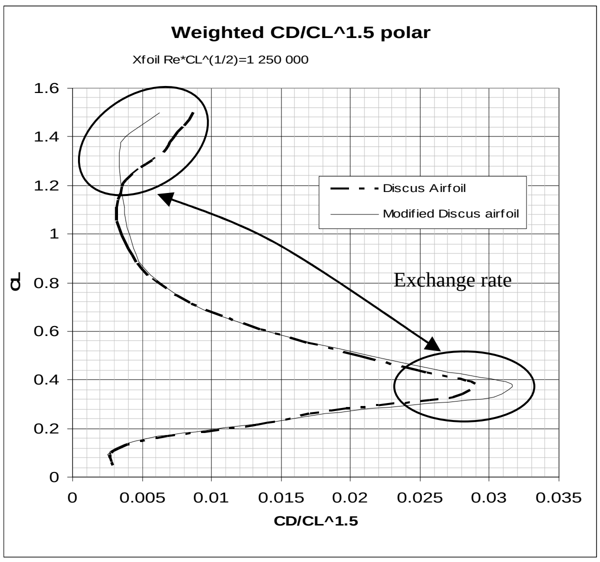

Figure 14 : Weighted CD/CL^1.5 polars