The Phoenix DF

- pushing the limits –

How it all began:

It was in the beginning of 2018 when Rollo Sommer of the Stream Team contacted me with a delicate question about designing an F5J aircraft.
Coming from F3K, knowing the latest in building technologies, especially about manufacturing full rohacell-core wings, he and Laurynas Ceskevicius (the manufacturer of the Concept CX5 DLG) wanted to transfer their knowledge to other air sports classes.

At the time I haven't put any efforts in designing an F5J plane yet and thought that the available planes on the market were manifold. However, Rollo was very persistent especially with his wish to create "something special".
A year or so before he was trying to widen the envelope with a new F3K-design called "The Flare" which incorporated leading edge and trailing edge flaps. This plane featured a wing with regular trailing edge flaps and additionally leading edge flaps (so called "front-flap") and both were controllable independently.
As Rollo is an airline pilot in his day job, he understands that these "front flaps" can provide extra lift, which can of course be necessary and helpful on heavy aircraft. For me it was very clear that leading edge flaps also produce an extra amount of drag, which might reflect a too big a penalty for an F5J aircraft.
I will try and give some insight into this a little later in this article.

Nevertheless, this "thinking out of the box" signalled to me, that the Stream Team was definitely ready and willing to break new ground and try something out of the ordinary.
However, I didn`t want to see this opportunity as a mere experiment, but rather as something that would be a real challenge. Of course, I wanted to avoid that the work that would be put into this aircraft would be seen as just a "phase of experimentation". It was actually important to me, that possibilities that would be worked out would actually be realizable.
The Stream Team had assured that it is also willing to take unconventional paths and bring them to series production readiness.
In a way, this was the starting point for the development of the double flap principle.

The idea behind the "double-flap":

At the beginning one has to be clear to recognize at which airspeeds, respectively lift coefficients an F5J model flies most of the time. It is certainly not an exaggeration to say that an F5J model spends 90% of its "lifetime" circling in thermals. Accordingly it is important to know at which coefficients of lift an F5J model flies while thermaling.
The diagram (Fig.01) shows the relationship between airspeed and lift coefficient for different model categories.

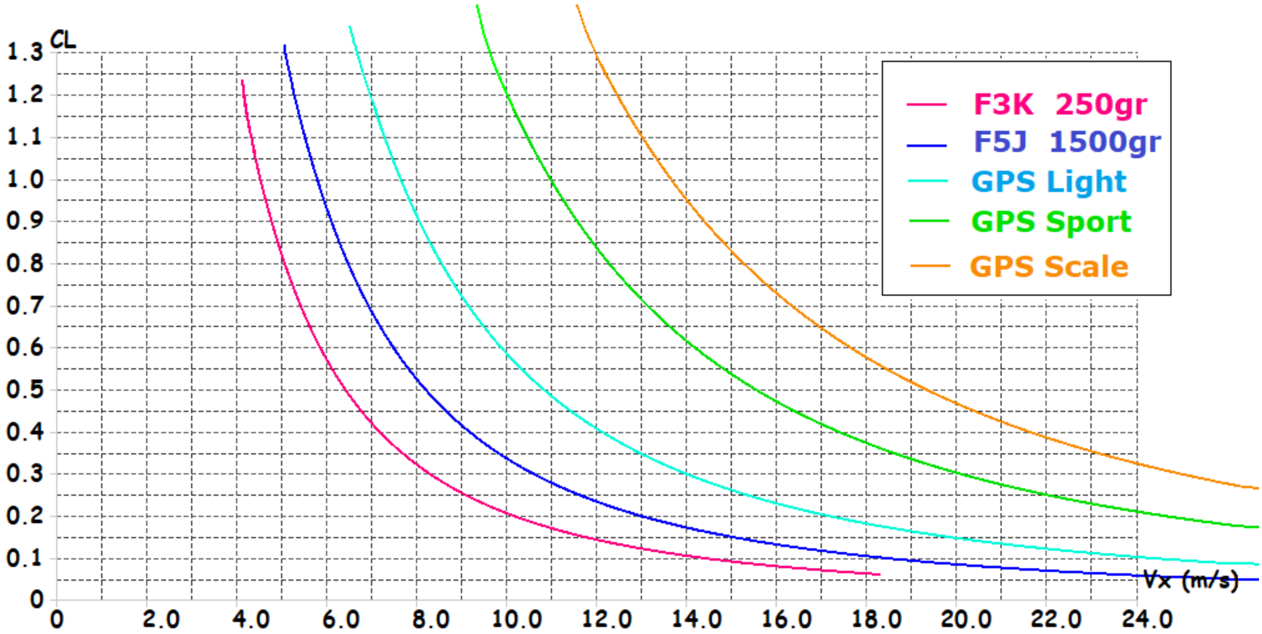


Fig. 01: relationship between CL and Airspeed for straight line flight.

Here it quickly becomes clear what kind of influence the All Up Weight of the plane, or rather its wing loading has on this relationship. It must also be mentioned that when thermaling, the respective bank angle has a significant influence on this – the steeper the bank angle, the greater the necessary lift coefficient at a given airspeed.

If we now take a look upon the range in which we will fly most of the time, we will find out that this ranges between CL 0.7 and CL 1.3. Therefore optimization of the performance parameters of an F5J model should primarily take place precisely in this range.

Figure 02 visualized this range.

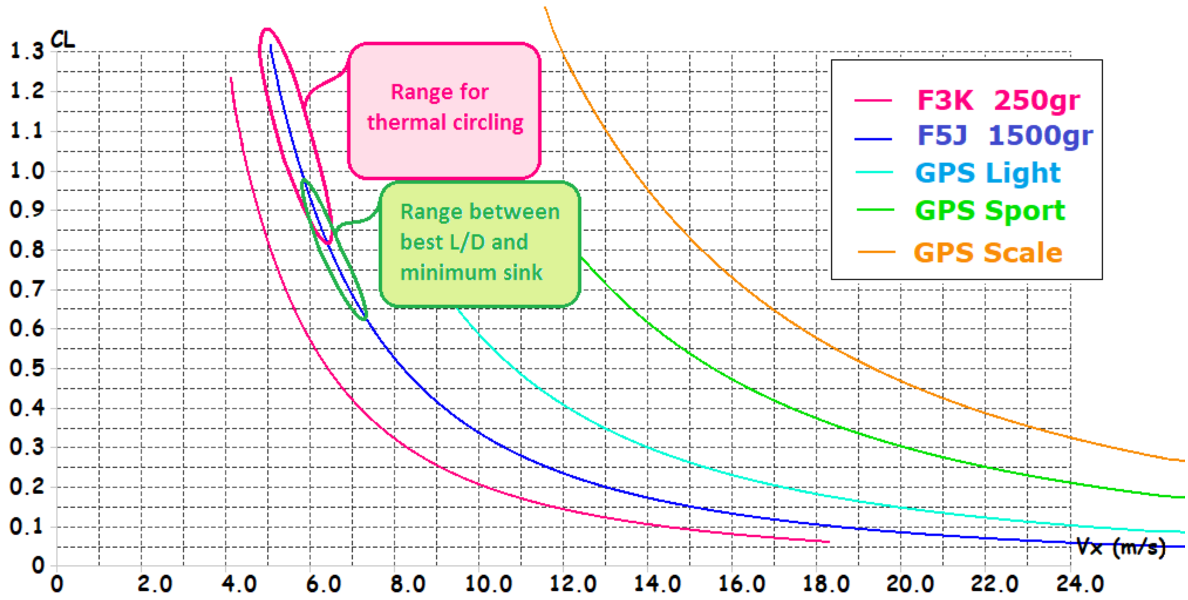


Fig. 02: operating range for 90% of an F5J models flight envelope.

Therefore, optimization of the performance parameters of an F5J model should primarily take place precisely in this range. This now raises the question of how to optimize the performance of an F5J model in the CL range around 0.95?
It stands to reason that as much drag as possible should be saved in this range in order to maximize the glide ratio, which is an important characteristic for quantifying the performance parameters of an aircraft. The glide ratio is expressed by the ratio of lift to drag (L/D), and it therefore quickly becomes apparent that a reduction in drag while maintaining the same amount of lift will result in an increase in glide ratio.
Another important characteristic is the so-called Endurance parameter, which is expressed by the following relationship: $L^{(3/2)}/D$.

The endurance parameter indicates how fast an aircraft can climb with a certain amount of energy, or how long it can remain in the air from a certain altitude without any energy input. Since the drag is as well below the fraction line here, any reduction in drag also leads to an increase in the endurance parameter.

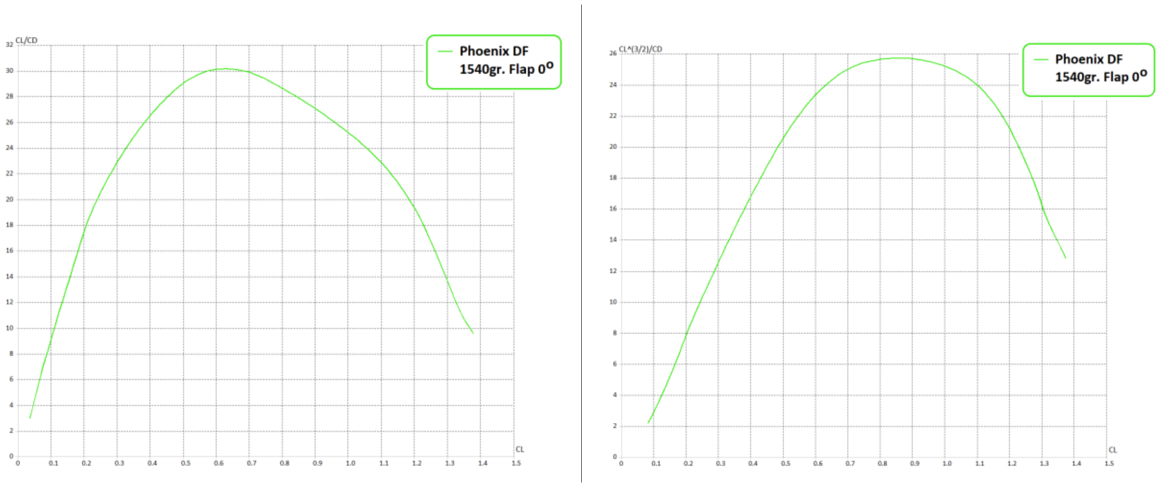


Fig. 03: Glide ratio and Endurance-parameters over CL

In the diagrams under Fig.03 you can see the glide ratio curves as well as the endurance parameter curves for a clean wing configuration, i.e. with the flaps in zero position.
If the camber is increased by a flap deflection, the primary goal is to increase the glide ratio and the climb rate. The proportion of lift should therefore be increased to a greater extent than the proportion of drag. The goal should be to increase the performance parameters as much as possible, and to do so within the widest possible lift range.

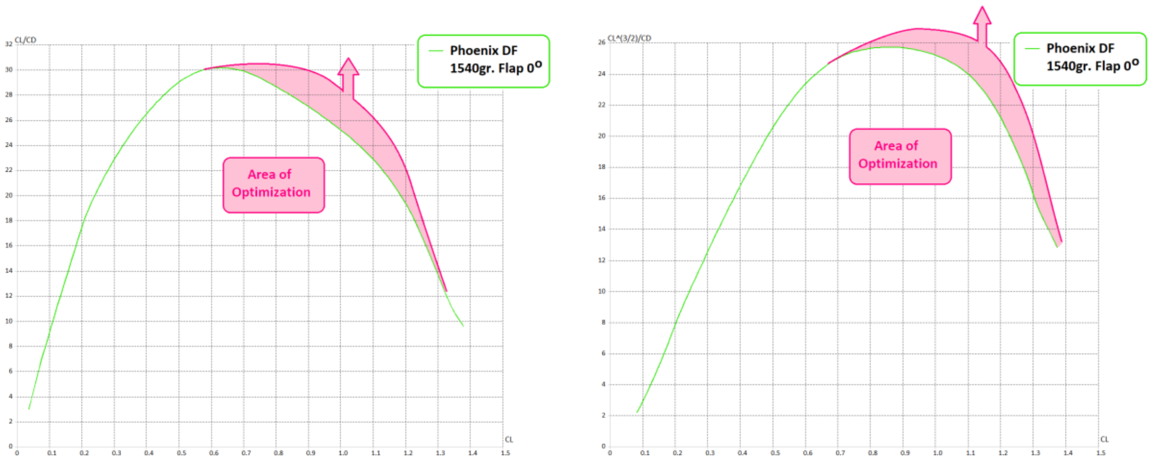


Fig. 04: beneficial areas of optimization

Fig. 04 illustrates this with the area marked in pink. When optimizing the flap deflections, care should be taken to ensure that the performance parameters increase over as wide a CL-range as possible. The arrow indicates the direction of the desired changes.
From this preliminary consideration, it is clear that the goal here is not so much to maximize the maximum possible lift coefficient, but to optimize the performance parameters within the most flown ranges. This applies not only to the setting of the various flight phases, but equally to each aileron deflection and elevator (snapflap!) deflection. Saving drag on each aileron and elevator deflection can mean immense drag savings, as F5J flying usually involves extremely high levels of control inputs, especially during "low level thermaling". Because an F5J plane most of the times sees excessive changes in throws (camber and aileron throws), it is important to safe as much drag as possible while moving the sticks.

Since there are limits to wing planform development (the rules allow a maximum span of 4000mm, which with modern construction technology allows reasonable aspect ratios between 19 and 21), we wanted to give priority to optimizing the airfoil and flap geometry in the development of the Phoenix DF to save further drag.

Developing the double flap solution:

Fortunately, F5J models fly at low speeds, and thus at relatively small Reynolds numbers. With these small Reynolds numbers, long laminar flow lengths on the airfoils are not primarily necessary to save drag. Rather, attention must be paid to minimizing the size and development of laminar separation bubbles where laminar-turbulent transition occurs.
A now common technique is to adapt the flap chord to the respective aerodynamic conditions. Nowadays you often see relatively wide flaps on many F5J models - these are usually also referred to as "bigflap" models.
If long laminar flow lengths are not necessary, then this is actually an effective way to save drag on flap deflections.
Here we can start a closer look at this issue.
The following graphics show three flap concepts.

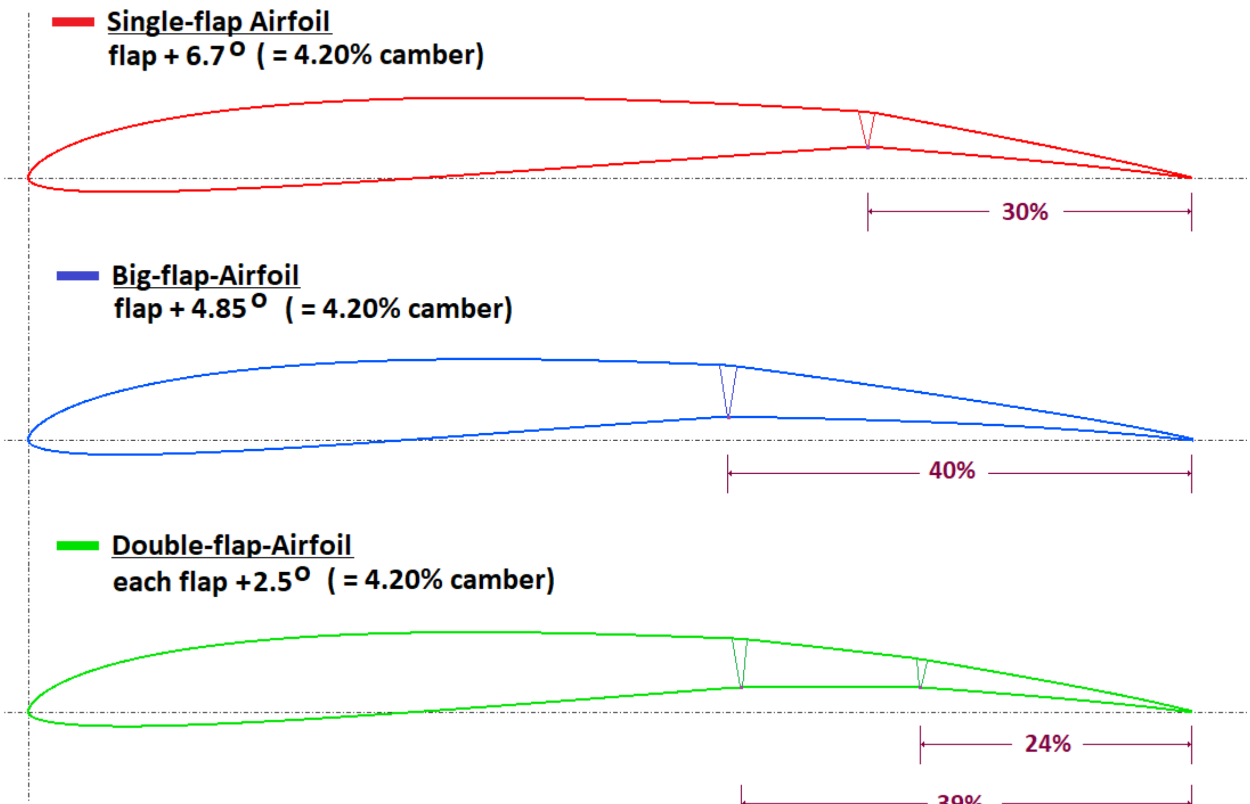


Fig. 05: Common flap arrangements for F5J models and the "double-flap-solution".

Typical F5J airfoils are shown in Fig.05, all of which achieve a basic camber of 4.2% by means of flap deflection.
The airfoil shown in red is a "single-flap-airfoil" and requires 6.7 degrees of flap deflection at 30% flap chord to achieve the 4.2% camber.
The airfoil shown in blue is called "Big-flap-airfoil" and requires 4.85 degrees of flap deflection at 40% flap chord.
The airfoil shown in green has two flaps. Both show 2.5 degrees of flap deflection, with the forward flap hinge at 39% chord and the rearward flap hinge at 24% flap chord.
This airfoil will be called "double-flap airfoil" from now on.

The airfoils are used at about 25% of the half span location of an F5J model and operate at 20gr/dm². Accordingly, they operate at a Re*sqrtCl value of about 90000. The interesting operating range for thermaling lies in the already mentioned CL ranges around CL = 0.95.

Examining the glide ratios of each airfoil at the respective operating points will show following results:

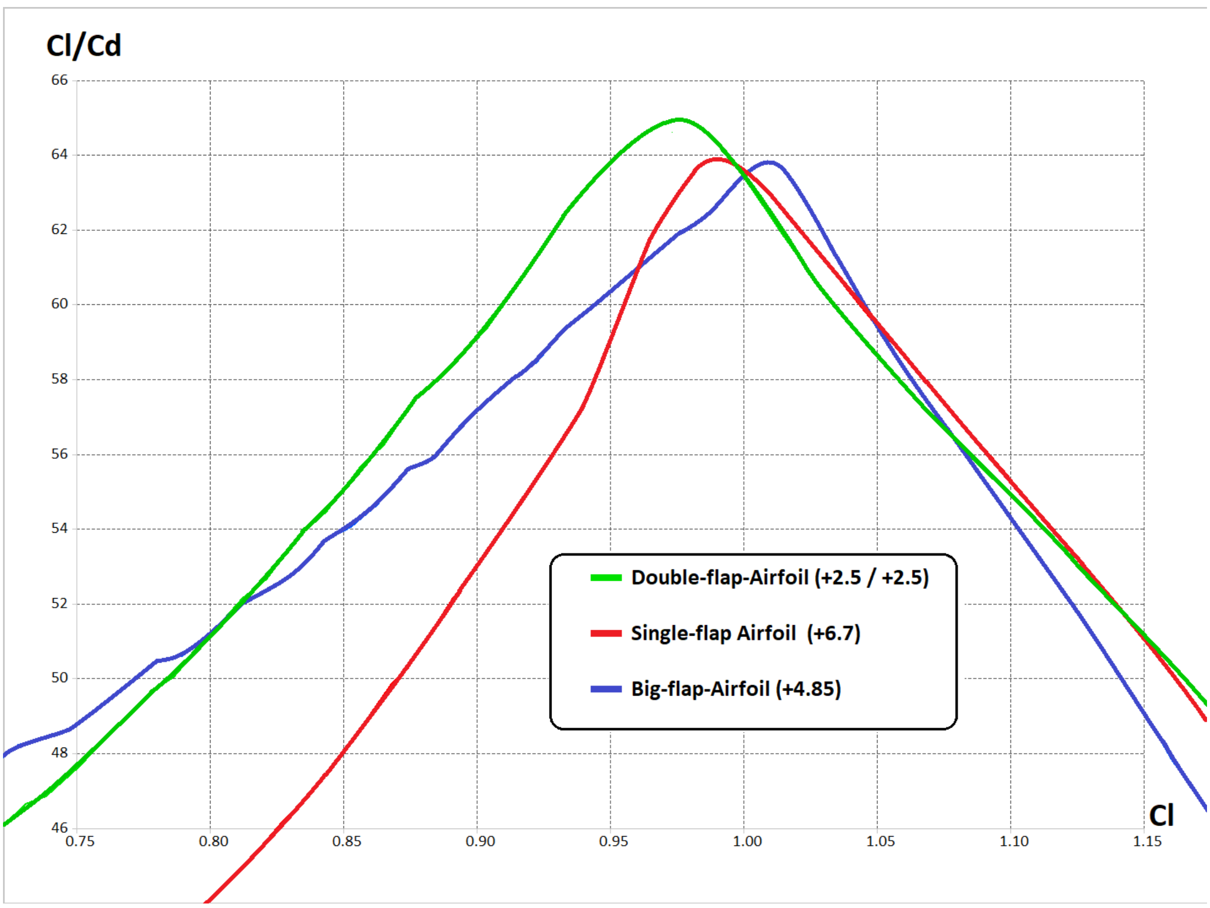


Fig. 06: LD-values of the examined airfoils in a Cl-range between 0.75 and 1.15

It can be seen that the double-flap airfoil achieves the highest airfoil glide ratio and the widest maximum of high glide ratios (i.e. high airfoil glide ratios over a wide range of lift coefficients) compared to the other two airfoils here. If we look upon the standard polar view (lift over drag polar), the graphs look like shown in Fig. 07.

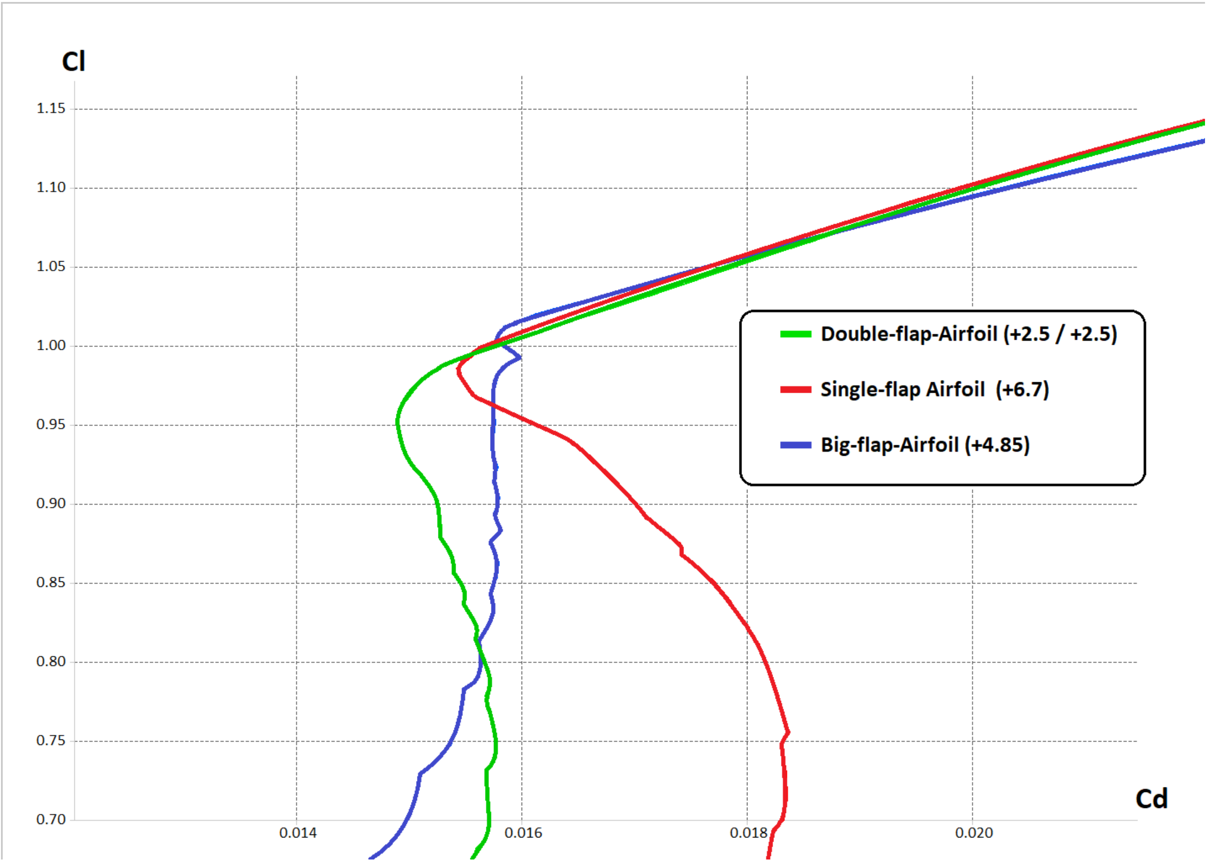


Fig. 07: Cl/Cd Diagram with respective polars for the observed airfoils

It is quite impressive to see that the double-flap airfoil has a clear drag advantage in the Cl-range between 0.8 and 1.0 in this flap configuration.
It is also clearly visible, that the single flap airfoil shows the most extensive drag rise due to the flap deflection between these three compared airfoils. Accordingly, a somewhat more detailed analysis is worthwhile here.

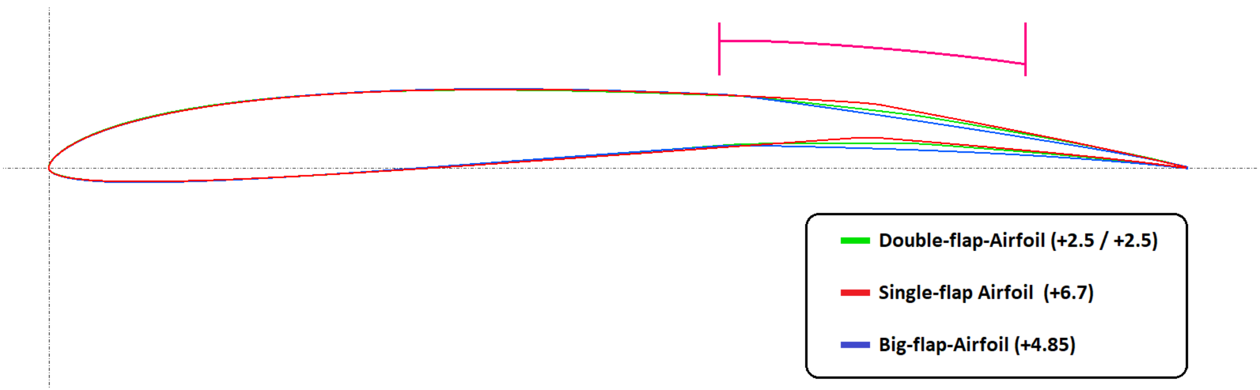
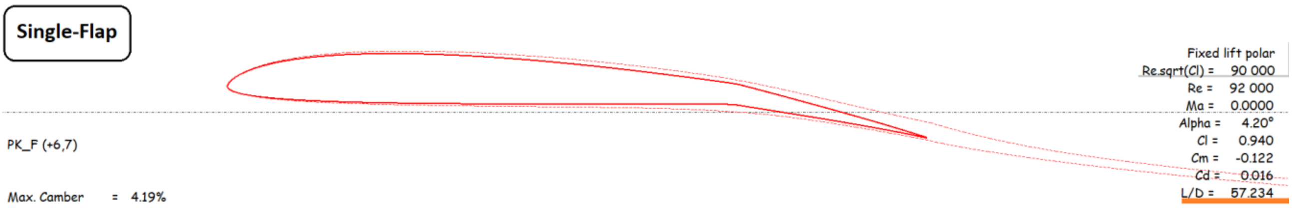
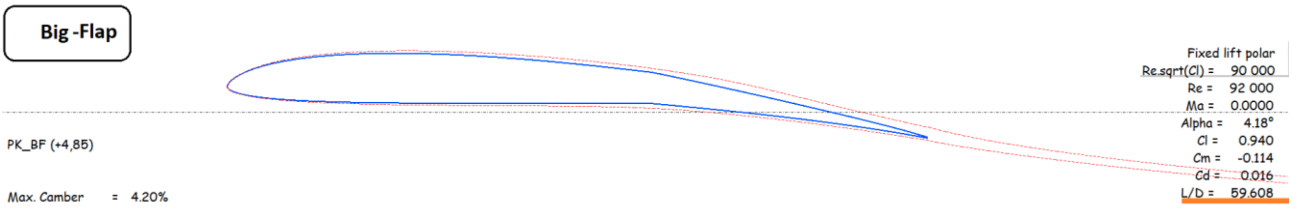


Fig.08: Overlay of the airfoils geometries

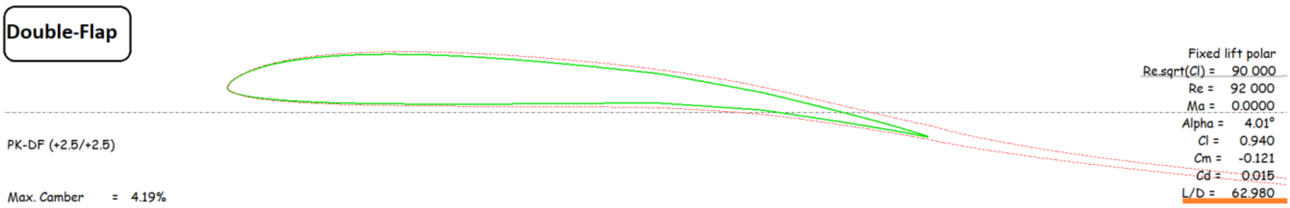
A look at the curvature of the upper side of the airfoils (especially in the area marked in pink in Fig. 08) shows very well how strongly a flap deflection can cause kinks in the contour of the airfoils. The discontinuities caused by the kinks are most noticeable in the single-flap airfoil (red airfoil). Even in the big-flap airfoil (blue airfoil), a pronounced kink is still visible at the position of the flap hinge. The contour of the double-flap airfoil (green airfoil), however, shows a relatively steady curvature of the surface, which is due to the fact that two smaller kinks cause less overall discontinuity than one larger one.
At this stage it is rather interesting to observe the aerodynamic boundary layer especially in the area of the kinks in the airfoils surface caused by the flap deflections.



*<u>Fig. 09:</u> Boundary layer on single-flap airfoil at Cl = 0.94 and Re*sqrtCl = 90000*



*<u>Fig. 10:</u> Boundary layer on big-flap airfoil at Cl = 0.94 and Re*sqrtCl = 90000*



*<u>Fig. 11:</u> Boundary layer on double-flap airfoil at Cl = 0.94 and Re*sqrtCl = 90000*

Fig. 09, Fig. 10 and Fig. 11 show the boundary layers on the examined airfoils at a Cl of 0.94. The boundary layer is indicated with the red dashed lines. It is very well visible how the thickness of the boundary layer increases with the downstream location and shows the transition from laminar to turbulent flow. The larger the laminar separation bubbles in this transition area are, the higher the resulting drag will be.

With the red single-flap airfoil, the resulting thicker boundary layer in the wake of the flap kink can be seen very well. This even leads to a thicker turbulent boundary layer at and behind the trailing edge of the airfoil. At this point of operation, this airfoil shows a glide ratio, i.e. a quotient of lift and drag coefficients, of 57.234.

In the same operating point the big-flap airfoil shows a glide ratio of 59.608, hence suffers less drag due to laminar separation bubbles. The thinner boundary layer is clearly visible and the thickness of the wake behind the trailing edge clearly appears to be less. Yet the presence of the laminar separation bubble right downstream of the flap kink is still detectable.

However, the double-flap airfoil handles the boundary layer on the upper side of the airfoil in a more gentle way. In this case separation bubbles certainly exist as well, but they remain smaller in size due to the more homogeneous airfoil contour. The savings in drag result in an airfoil glide ratio of 62.98 in this operating point.

With these initial encouraging results, the next step was to investigate a variety of flap angles to estimate the actual improvements in glide ratio and endurance parameters based on an envelope of all individual polars.

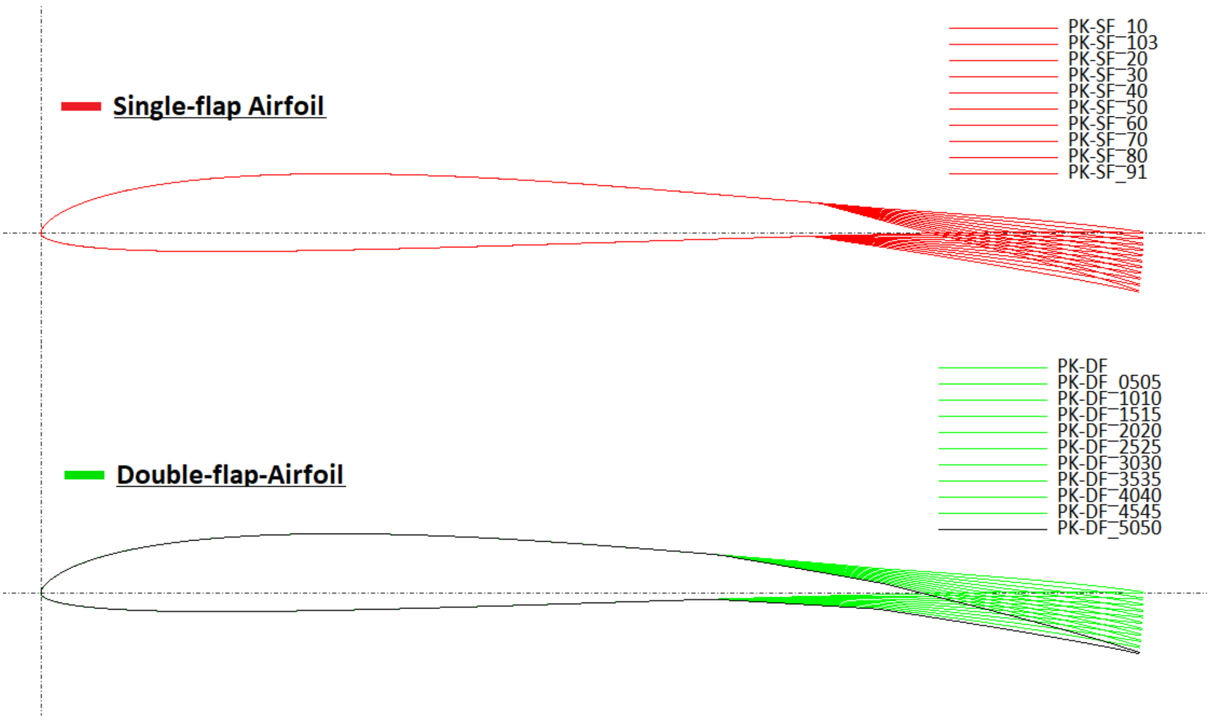


Fig. 12: Comparison of flap angle envelopes

The envelope so to say, is the wrapping graph, which connects all polars of the individual flap angles.
In Fig. 13 the envelope of all examined flap angles is depicted with the bold lines, red for the single-flap airfoil, green for the double-flap airfoil. The thin dashed lines represent the polars for each flap setting.

Glide ratio comparison

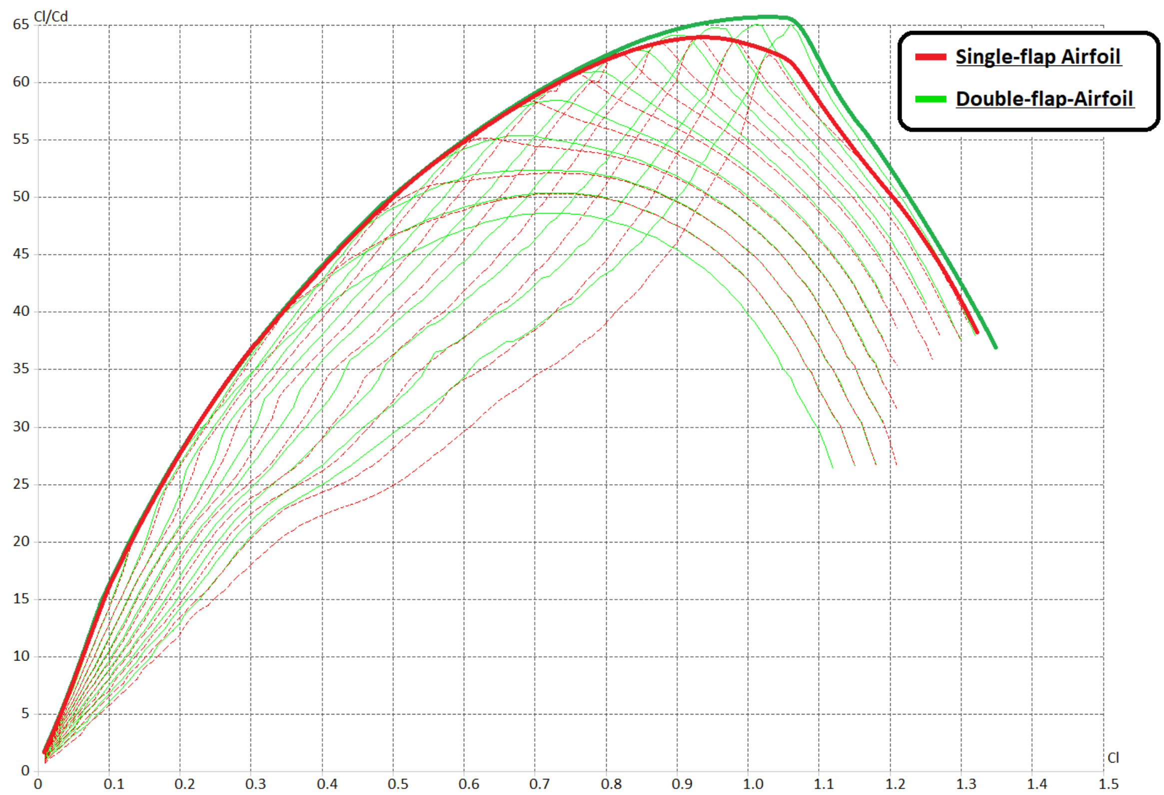


Fig. 13: plot of airfoil glide ratios for single-flap and double-flap airfoil over lift coefficients for various flap angles.

In fact, as already noted in Fig. 04, an increase in performance parameters can be observed in the targeted CL range between 0.8 and 1.3. The double-flap airfoil shows higher L/D and thus better performance in this range.

Endurance parameter comparison

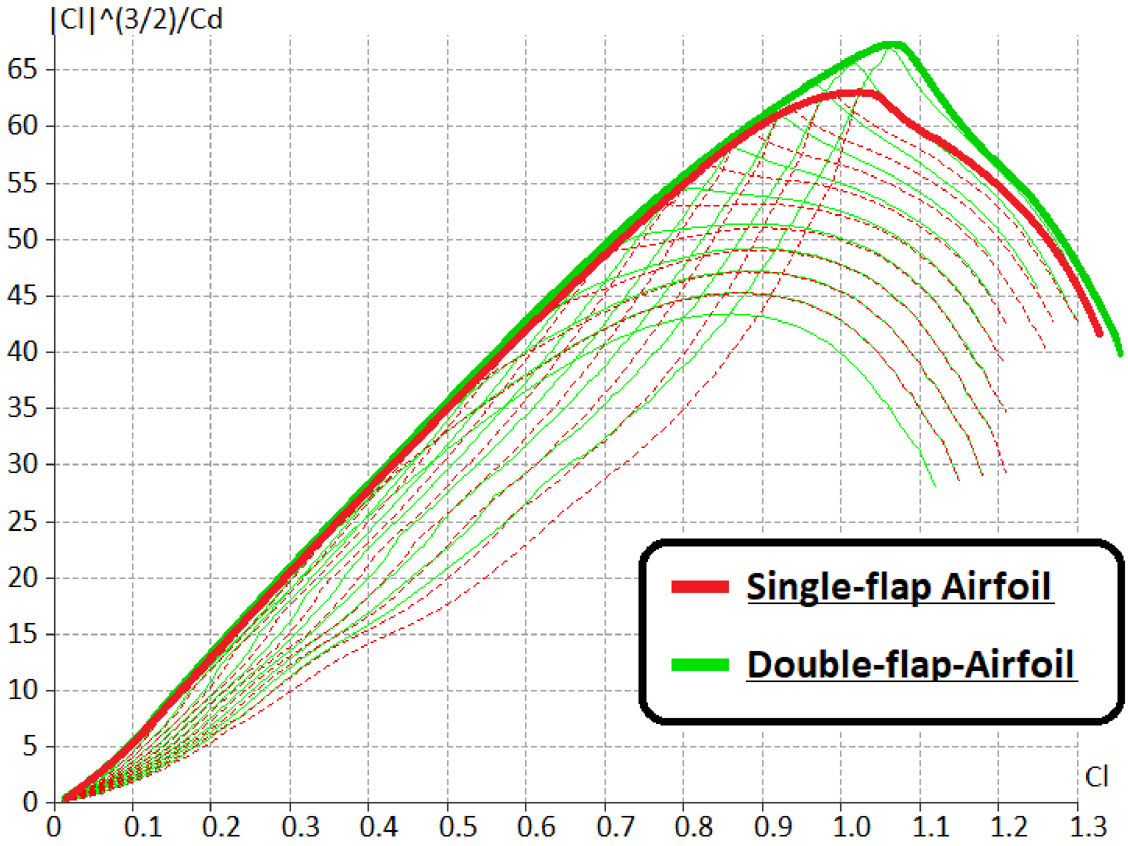


Fig. 14: plot of airfoil endurance parameters for single-flap and double-flap airfoil over lift coefficients for various flap angles.

Looking at the endurance parameters, the advantage for the double flap airfoil also becomes evident. Between CL= 0.9 and CL = 1.3, the double-flap airfoil achieves better values and especially between CL = 1.0 and CL = 1.1 a significant gain is noticeable. This means that the model with the double-flap wing can climb faster in thermals or circle tighter at steeper bank angles, or "hang" for a longer time in calm air when flown at the same wingloading. This double-flap arrangement also allows for slightly greater flap angles to be used. In the graph above flap settings up to +10 degrees (measured at the rearward segment of the double-flap) were calculated. In any case it is very strongly recommended to use "snap flap" in any flight mode. With this, the airfoils L/D parameters can be kept optimal when pulling or pushing the elevator (reflexing the wings trailing edge while pushing the elevator / cambering the wings trailing edge while pulling the elevator). If the plane will show excessive reactions to elevator inputs, I´d rather reduce the complete elevator throw than the "snapflap mixing ratio".
The insight on the potential of implementing a double-flap opens up a further field of optimization possibilities. What is the best ratio between the flap deflections of the forward and the rearward flap?

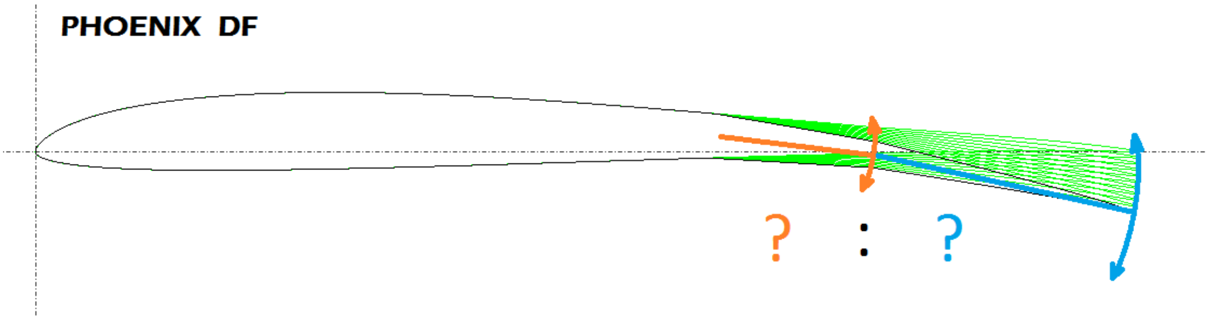


Fig. 15: finding the right mixing ratio between forward and rearward flap deflection

It was clear from the beginning that only one servo per double-flap should be used to control the double-flap. A “four servo wing” can be programmed without any problems, but installing four more servos would result in a significant increase in complexity as well as additional weight and significantly higher inertia of the complete wing.
Accordingly, mechanical kinematics for the linkage of the double-flap had to be designed to control the double-flap system.
Consequently the deflection proportions between forward and rearward flap must be set to a predefined ratio and this should, of course, be selected as optimally as possible out of aerodynamic reasons.
On the inboard part of the wing Reynolds numbers are higher and the boundary layer thinner and more stable in the sense of laminar separation bubbles. These are likely to occur less pronounced, which would allow a stronger curvature on the upper surface of the airfoil under flap deflection.
In this case a flap angle ratio from forward to rearward flap in the magnitude of 1:3 is still possible without a radical drag rise with increasing flap angles.
However, this doesn`t apply at all in the outboard parts of the wing close to the tip at lower Reynolds numbers. Here a ratio of about 1:2 seems much more beneficial in order not to stress the boundary layer too much, which might cause large and draggy separation bubbles due to a major pressure recovery close to the trailing edge area of the wing.

In the end 8 transitional airfoils featuring double-flaps were designed to account for the different Reynolds numbers regimes at their respective spanwise position.
In order to keep the lift distribution as homogeneous and slightly over elliptical as possible, even under flap deflections, a constant ratio of forward to rearward flap of 1:2.1 was chosen. This means that the rearward flap automatically deflects 2.1 degrees with each degree of forward flap deflection.

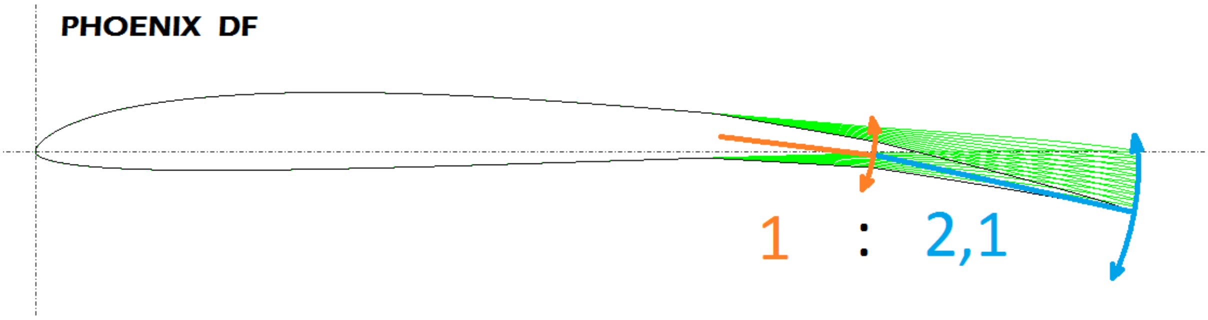


Fig. 16: optimized coupling ratio between forward and rearward flap

The next complex step was to develop a suitable and at the same time optimized wing planform, which was designed to incorporate the use of double flaps. It is not sufficient in this case to simply place two hinge lines in an arbitrary manner into the wings planform. This can inevitably lead to (percentage-wise) inconstant flap chords along the wingspan.

If a wing is configured with a "normal" flap, the planform can be designed in such a way, that the hinge line is straight and the trailing edge flaps can be designed with identical chord depth percentage – regardless of the outline of the wing planform.
With a double-flap solution equal chord depths for both flaps are only possible when choosing a single taper or rectangular planform. In sophisticated elliptical planforms this reflects a geometrical challenge where certain concessions need to be made.

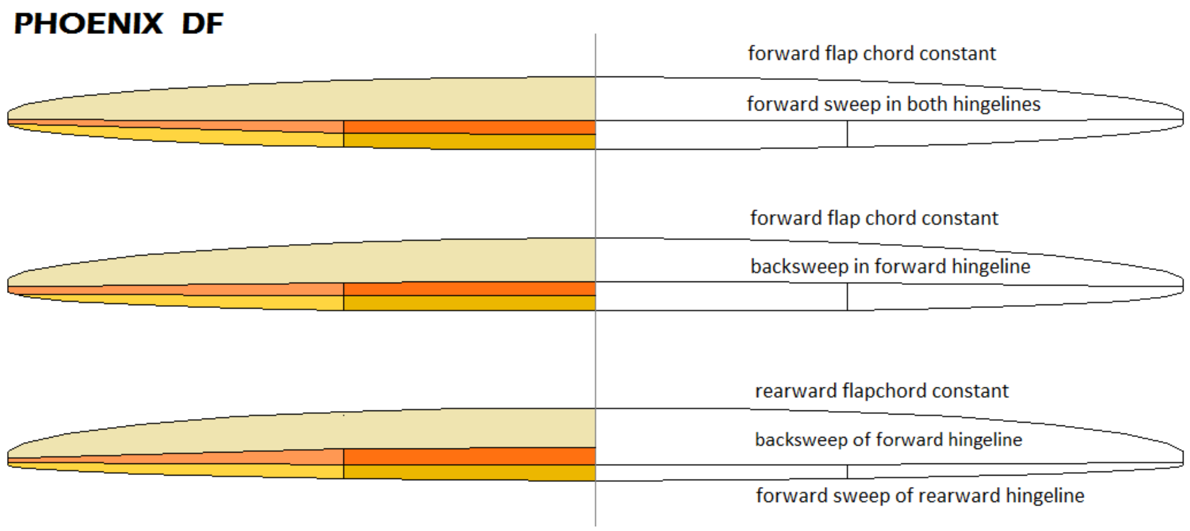


Fig. 17: development of an efficient wing planform for incorporating the double-flap

The sketches in Fig. 17 illustrate the challenges in developing the wing planform for the double-flap. The upper outline shows a planform in which the forward hinge line was designed straight and with a constant percentage chord. To implement an as straight spar as possible, the resulting sweep in both hinge lines is forward. This leads to very unequal distribution in flap chords, especially in the rearward flap.
The centre outline also features a planform design with a constant percentage chord of the forward hinge line, but this time the forward hinge line is swept back. The disadvantage of this solution is that the spar must be swept back significantly, which is detrimental to the bending-torsion coupling. Furthermore, with this design, the rearward flap ends well before the wing tip, so that the very outboard wing doesn´t feature a double-flap anymore and the flap chord of the rearward flap continuously decreases to 0% beforehand.
The final solution to the problem was to keep the rearward flap hinge line straight and as constant in chord as possible, and then add a slight forward sweep to it. This led to an as constant forward flap chord after arranging the correct back sweep of the forward hinge line.
At the end only minor back sweep to the spar location was the result to this solution.
The airfoils feature kinks in the surface on the rearward flap hinge, so even this was to take into account when designing the actual planform.
Finally the planform, the airfoils and the hinge lines were coordinated and, above all, great importance was addressed to ensuring the "difficult-to-shape" wing tip met all geometric and aerodynamic requirements. The final flap chords can be seen listed in Fig. 18.

PHOENIX DF

Flapchord-distribution

Chord	% rearward flap	% forward flap
240.0mm	24%	40.000%
235.3mm	24%	39.121%
221.0mm	24%	39.000%
198.0mm	24%	37.811%
163.4mm	24%	37.613%
122.6mm	24%	39.000%
83.7mm	22%	41.258%
48.0mm	18%	49.556%

Fig. 18: actual flap chord distributions of the PHOENIX DF

Just as a side note, I would like to briefly talk about the leading edge flap mentioned at the beginning. Out of interest to take a closer look at this configuration, I also examined a “front-flap airfoil”.

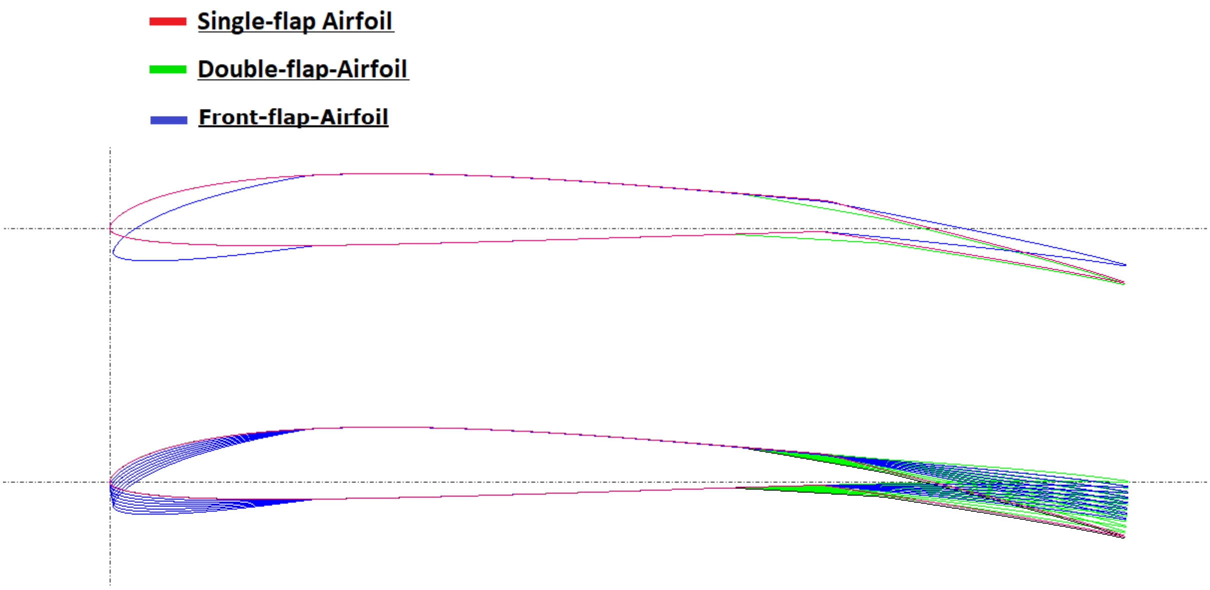


Fig. 19: comparison of double-flap and front-flap airfoil

In Fig.19 the examined “front-flap” airfoils is also depicted in blue. It features a 30% wide normal flap and a 22% wide leading edge flap. This leading edge flap produces a harsh kink in the airfoils surface (upper and lower) when deflected. This happens in an upstream location where the natural flow boundary layer is laminar, at least until very high lift coefficients are reached and the laminar-turbulent transition has moved close to the upper kink in at the front flaps hinge line. Even small deflections of the front flap can trip the boundary layer at this upstream location because of the discontinuity in the airfoils surface. The resulting polars and the envelope of the individual flap settings are shown in the graphs of Fig. 20 and Fig. 21.

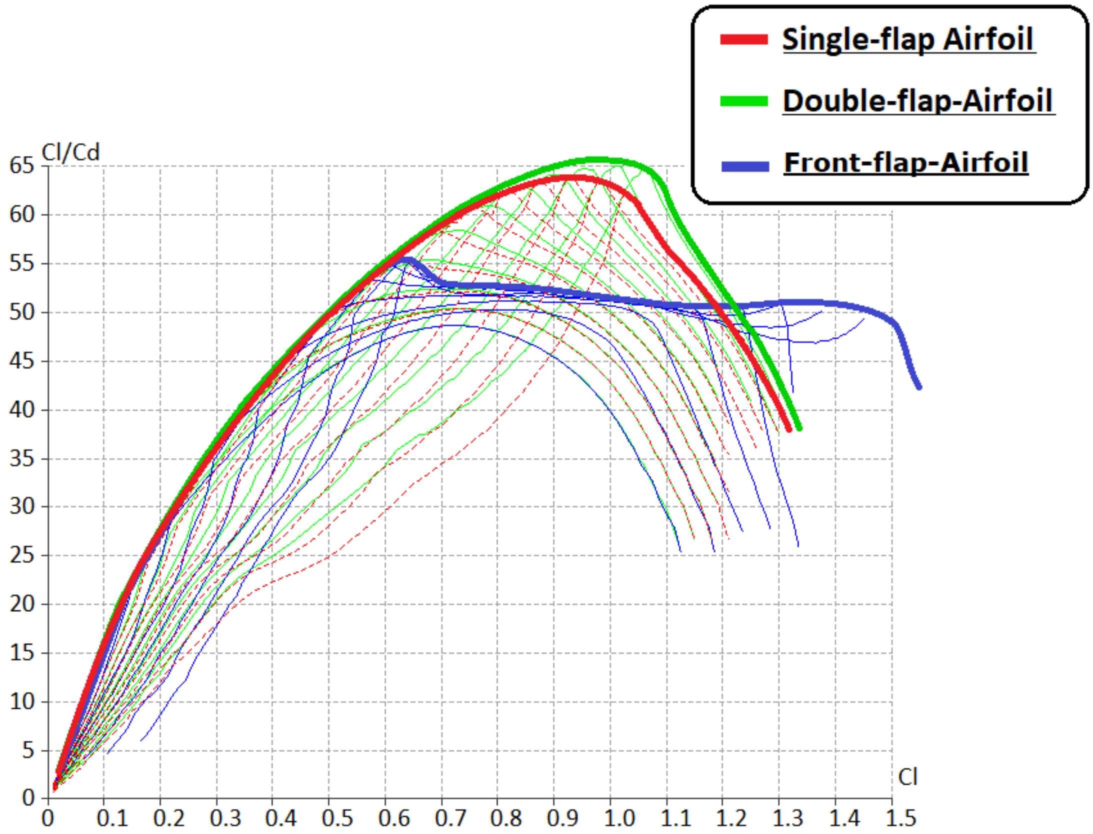


Fig. 20: plot of airfoil glide ratios for single-flap and double-flap and front-flap airfoils.

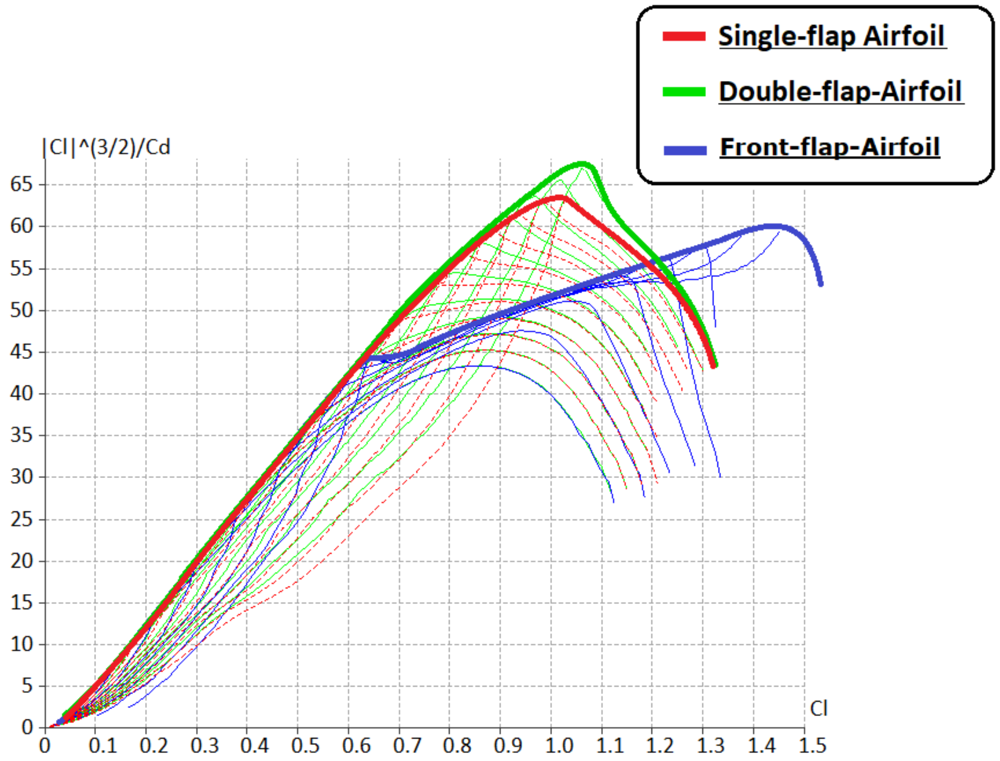


Fig. 21: plot of airfoil endurance parameters for single-flap and double-flap and front-flap airfoils.

It is obvious that the front flap airfoil really can reach very high lift coefficients and show quite good performance above lift coefficients of 1.3. So for heavy aircraft, which needs to produce high lift at low speeds, this actually can be a considerable solution. But as so much importance is given to optimizing the CL range between 0.9 and 1.3 on an F5J airplane, one must acknowledge that the front flap solution really suffers in exactly that range.

In conclusion, I would like to summarize the most important key poınts and findings of the development of the PHOENIX DF:

- Optimizing performance on an F5J aircraft is primarily about optimizing L/D and $L^{(3/2)}$/D in the high CL-range. It is not so much about only optimizing the maximum achievable lift coefficient.

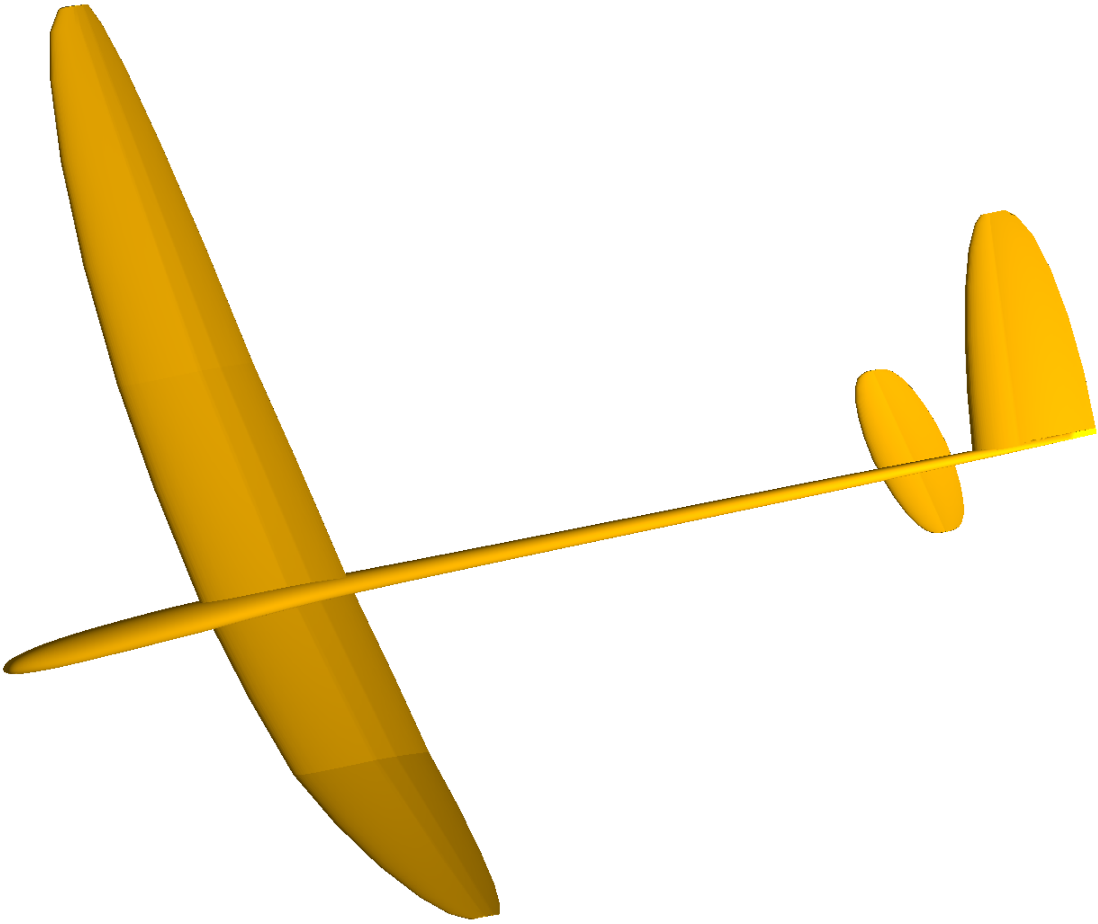
- Because an F5J plane most of the times sees excessive changes in throws (camber and aileron throws) it is important to safe as much drag as possible while moving the sticks.

- A plane which saves drag at a given amount of lift, will glide further (L/D) and climb faster ($L^{(3/2)}$/D).

- A double flap will work for aircraft, where long laminar airflow is not necessary in the first degree. This counts for fairly slow flying aircraft. In this case the moveable part of the wing can get larger in chord wise direction.

- The double-flap arrangement is Increasing lift at a lower drag penalty.

- The best solution would be to have a “morphing wing”, but under the condition that this “morphing” can be perfectly controllable. Here an exact change of contour is required, which is not the same thing than “just bending” the airfoils’ surface! ;)



<u>Fig. 22:</u> The PHOENIX DF with visible hinge lines on the double-flap wing.

I wish all the PHOENIX DF pilots and PHOENIX DF "pilots to be" lots of fun and good success with this sophisticated glider.

Philip Kolb